Diploma thesis

Evaluation of the nitritation performance of a Continuously-Stirred-Tank-Reactor and a Moving-Bed-Biofilm-Reactor treating reject water

Carried out for the purpose of obtaining the degree of Dipl.-Ing.,
submitted at TU Wien,
Faculty of Mechanical and Industrial Engineering,

by

Phichaya Choonuan

Mat.Nr.: 1454467

Under the supervision of
Ass.Prof.Dr.techn. **Svardal Karl**
Dipl.-Ing. Dr.techn. **Parravicini Vanessa**

Institute for Water Quality and Resource Management
Vienna University of Technology
Karlsplatz 13/ 226, A-1040 Vienna

Affidavit

I confirm that going to press of this thesis needs the confirmation of the examination committee.

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such.

I confirm, that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.

Vienna, May, 2018   _____

Signature

Abstract

Wastewater treatment plants are highly energy consuming and can contribute up 1 % of a city's energy consumption. A high amount of this energy can be saved by applying an appropriate operation mode. Anaerobic digestion of influent organic matter can produce biogas and the overall energy consumption can this way be reduced. Remaining sludge after anaerobic digestion is dewatered and results in an effluent, called reject water. Reject water or Sludge Dewatering Effluent (SDE) needs further treatment, since it still contains a high amount of ammonium, which needs to be removed. Pretreatment of reject water in the side-stream can save additional energy. The potential for the energy saving lies in a higher aeration efficiency in side-stream compared to main-stream. Moreover, when stopping the conversion process from ammonium to nitrite (nitritation) and further to nitrate (nitratation) at the first conversion step, less COD is required in the denitrification process of a 2-stage wastewater treatment plant. A higher amount of COD in the sewage sludge leads to a higher biogas yield in anaerobic digestion. The present thesis compares a lab-scale Continuously-Stirred-Tank-Reactor (CSTR) and a Moving-Bed-Biofilm-Reactor (MBBR) regarding their nitritation performance. It will mainly focus on the influencing parameters like sludge age and free ammonia/free nitrous acid inhibition in order to achieve partial nitritation in SDE side-stream treatment. Partial nitritation is achieved in CSTR down to a temperature of 15°C. MBBR is able to treat up to 3 times the ammonium load of a CSTR and also showed stable nitritation with even lower susceptibility towards changing operation conditions.

Table of content

Table of Figures

Table of Equations

1   Introduction

The thesis deals with the idea of improving the energy efficiency of wastewater treatment plants and to find a way of achieving a shift in converting wastewater treatment plants from energy consumers into energy producers.

More precisely it will deal with the biological treatment of the side-stream of a wastewater treatment plant. The side-stream describes the reject water, or sludge dewatering effluent (SDE) that emerges when anaerobically digested sewage sludge (conversion of organic matter into biogas) is dewatered to separate the sludge into a liquid phase (SDE) and a solid phase. The ladder is most commonly burnt in waste incineration plants. SDE, on the other hand, contains high concentrations of ammonium, slowly biologically degradable chemical oxygen demand (COD) and a relatively low concentration of suspended solids. The conventional method of SDE treatment is reintroducing SDE into the mainstream, where it leads to a higher energy demand for aeration in the activated sludge tank, a lower ammonium removal degree and a decrease in biogas yield when later on digested. A pre-treatment of SDE prior to reintroducing it into the mainstream could lead to some major energy savings, due to higher standard aeration efficiencies within the side-stream compared to main-stream. A further target is stopping biological nitrification process at the first step in order to achieve nitritation only. Hereby valuable COD is saved in the first stage of a 2-stage WWTP, which further leads to a higher biogas yield in the digestion of the sewage sludge. Moreover a higher amount of COD is available as a substrate for the denitrification process of a wastewater treatment plant.

A lab-scale plant is applied in order to perform experiments on the SDE side-stream treatment and to evaluate process parameters for the investigation period of 325 days. Two different methods for SDE treatment will be compared. In a Continuously-Stirred-Tank-Reactor (CSTR) microorganism are left in the bulk liquid, while the other method uses especially formed carriers with a relatively high surface area allowing the formation of a biofilm, also known as Moving Bed Biofilm Reactor (MBBR). The evaluation focuses on process parameters like maximum ammonium removal degree, ammonium loading rate, solid retention time (sludge age), pH-value, temperature, free ammonia (FA) inhibition, free

nitrous acid (FNA) inhibition and the influence of all these parameters in order to achieve a stable partial nitritation performance. Additional analyses based on OUR (Oxygen Uptake Rate) measurements will investigate the distribution of active biomass between bulk liquid and biofilm carriers. Laughing gas (N_2O) emission will be also part of the analysis plan, since its uncontrolled emission in the atmosphere has a major effect on the carbon footprint of sewage-treatment plants.

2 Theoretical Background

2.1 Microbiological processes

Municipal wastewater treatment plants consume up to 1 % of a city's electricity consumption. Therefore investigations on how to reduce these consumptions are of great interest. Engineers and scientists have come up with a special operation mode for modern wastewater treatment plants (WWTP), by which a considerable amount of the energy consumption can be saved.

In order to understand these energy reduction potential of a WWTP, we will have to take a closer look into microbiological processes relevant for SDE treatment and the main technical principles wastewater treatment plants are based on. This is followed by an introduction of the different operation modes of WWTP in order to understand the energy saving potential of a WWTP.

2.1.1 Nitrification

Nitrification is defined as the conversion of reduced inorganic nitrogen compounds to nitrogen compounds with a higher oxidation state. The most common process is the oxidation process of ammonium/ammonia (NH_4^+/NH_3) under aerobic conditions to nitrite (NO_2^-) and further to nitrate (NO_3^-) by different species of bacteria, respectively. Since ammonium is the major degradation product of nitrogenous compounds, the influent of a WWTP contains a high load of ammonium/ammonia. Therefore nitrification is a crucial process in for biological wastewater treatment (Baumgartner et al., 2016).

For natural ecosystems nitrification plays an important role in the nitrogen cycle, since it deals with the conversion of ammonia (product of degradation processes of dead biomass) to nitrate, which can be re-used by plants as a substrate (Zhang et al., 2009). A simplified version for nitrification processes can be described in two steps. The first step is called nitritation and is performed by a group of bacteria called ammonia-oxidizing bacteria (AOB). One species of this group of bacteria are e.g. Nitrosomonas.

The following second step is called nitratation, which is performed by nitrite oxidizing bacteria (NOB), e.g. Nitrobacter. Both bacterial groups are autotrophic organisms that normally work under aerobic conditions, meaning that they require dissolved oxygen (O_2) and carbon dioxide (CO_2) as a carbon source for their metabolic processes (Baumgartner et al., 2016; Helmer-Madhok, 2004).

Nitritation:
$$NH_4^+ + 1.5\,O_2 \rightarrow NO_2^- + H_2O + 2\,H^+ \qquad \text{Eq. 1}$$

Nitratation:
$$NO_2^- + 0.5\,O_2 \rightarrow NO_3^- \qquad \text{Eq. 2}$$

Nitrification:
$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + H_2O + 2\,H^+ \qquad \text{Eq. 3}$$
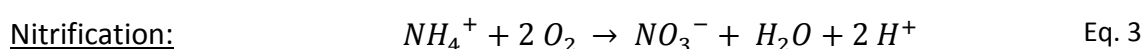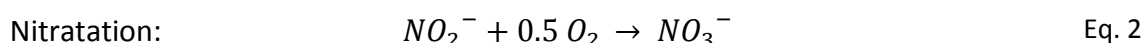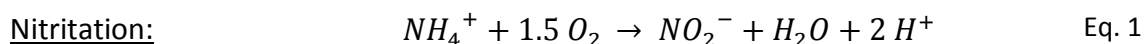
2.1.2 Denitrification

Denitrification speaks of the subsequent step, by which the conversion of priorly formed nitrate (NO_3^-) to nitrogen gas (N_2) takes place. Equally, the conversion of nitrite (NO_2^-) to nitrogen gas (N_2) is called denitritation. Both processes are carried out by heterotrophic bacteria under anoxic conditions and require organic carbon compounds as electron donors. The conversion can be described by the following simplified equations (Baumgartner et al., 2016; Helmer-Madhok, 2004):

Denitrification:
$$NO_3^- + H^+ \rightarrow 0.5\,N_2 + 2.5\,O + 0.5\,H_2O \qquad \text{Eq. 4}$$

Denitritation:
$$NO_2^- + H^+ \rightarrow 0.5\,N_2 + 1.5\,O + 0.5\,H_2O \qquad \text{Eq. 5}$$
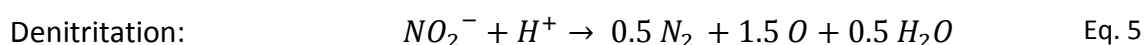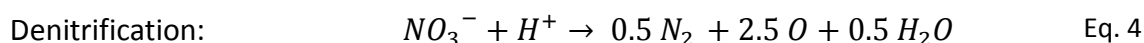
2.1.3 Anammox

Anaerobic ammonia oxidation (Anammox) is a rather novel discovered process and can occur in biological wastewater treatment under certain conditions. The responsible microorganisms, taking part in this conversion process, were discovered only a few decades ago in the 1980ies. Anammox bacteria are able to convert ammonium in a two-step process directly into nitrogen gas (N_2) without the usage of an organic carbon source, unlike in

denitrification. The process runs under anaerobic conditions and can simplified be divided into two steps (Strous et al., 1998):

Anammox:
$$NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow$$
$$1.02\ N_2\ + 0.26\ NO_3^- + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03 H_2O$$

Eq. 6
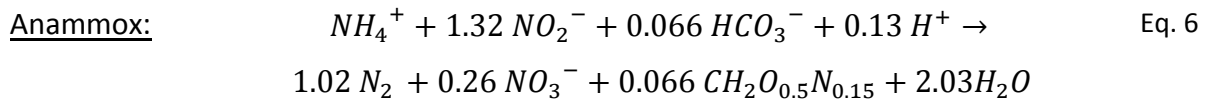
First ammonium (NH_4^+) is converted into nitrite (NO_2^-) under aerobic conditions and then nitrite (NO_2^-) together with ammonium (NH_4^+) is converted directly into nitrogen gas (N_2) and water (Baumgartner et al., 2016).

2.1.4 Anaerobic COD degradation

Anaerobic COD degradation (also anaerobic digestion) is a biochemical process, where specific microorganisms convert organic compounds under the absence of oxygen into biogas (mainly consists of methane and carbon dioxide). It represents an effective technique for the reduction of biomass volume as well as the stabilization of sewage sludge and other biodegradable material, while simultaneously recovering renewable energy in the form of biogas. Methane from biogas, when further upgraded, can be used for heat and electricity production, as transportation fuel, or can also be introduce into the natural gas grid. Sewage sludge for anaerobic digestion consists of the influent wastewater compounds and activated sludge that increases its amount due to growth of the biomass. In large WWTPs sewage sludge is passed on to the digester, where anaerobic digestion produces biogas and stabilizes the sludge before disposal (Uçkun Kiran et al., 2016).

2.2 WWTP configuration schemes

2.2.1 Single - stage WWTP

The conventional operation mode is represented by a 1-stage WWTP. It consists of an activated sludge tank (aeration tank) with an anoxic part at the prior part of the tank, where denitrification takes place, followed by the larger aerobic part, where nitrification takes place. The aeration tank is followed by the clarifier where the sludge flocks are separated

from the treated wastewater by sedimentation. The treated wastewater phase leaves the plant as the effluent. The settled solids are partly returned to the activated sludge tank in order to adjust a certain sludge age. The exceeding surplus sludge is extracted and proceeds to the digester for stabilization (Baumgartner et al., 2016).
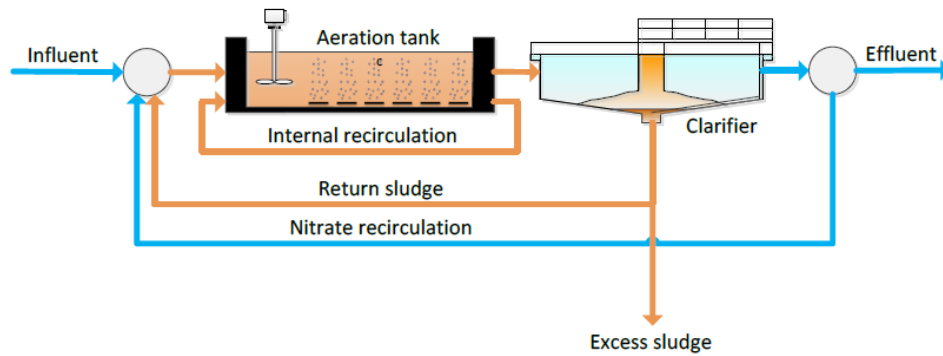
Figure 1: Flow scheme of a 1-stage WWTP (Baumgartner et al., 2016)

2.2.2 2-stage WWTP

2-stage WWTPs apply two separated aeration tanks and clarifiers, resulting in two completely separated sludge streams. While the 1st stage is responsible for the COD - removal, the 2nd stage takes care of the nitrogen removal. The high-loaded first stage only requires a short sludge age for biological COD conversion, while in the low-loaded 2nd stage a higher sludge age is required. A bypass from the influent to the 2nd stage supplies the required organic carbon for denitrification, if in the first stage too much COD is removed (1st stage – COD removal) (Baumgartner et al., 2016).
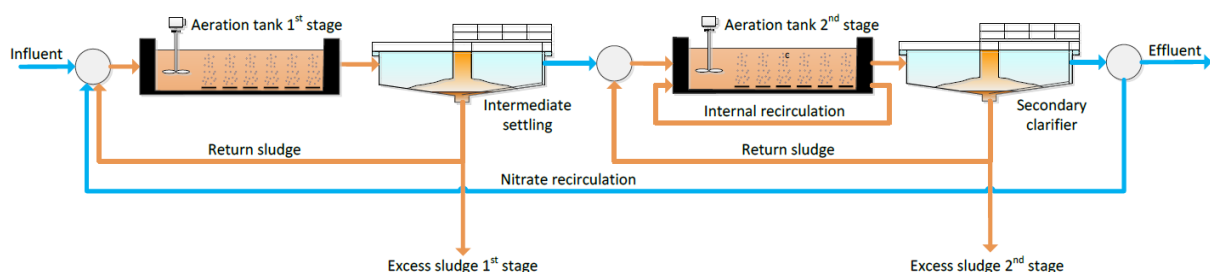
Figure 2: Flow scheme of a 2 stage WWTP (Baumgartner et al., 2016)

2.2.3   Advanced 2-stage WWTP

An enhanced version of a 2-stage WWTP targets a COD extraction in the influent for direct conversion to biogas through anaerobic digestion. Usually COD oxidizes in the aeration tank, where precious organic carbon content is consumed, instead of being used for the energy production through anaerobic digestion forming valuable biogas (Baumgartner et al., 2016).

This configuration additionally introduces a partial sludge stream from the 1st stage to the 2nd stage of the WWTP (similar to the bypass from the influent to the 2nd stage in the previous configuration). By this means organic carbon (required as a substrate for denitrification process) is being supplied in the 2nd stage. Another partial sludge stream from the 2nd stage to the 1st stage ensures a sufficient biomass supply in the 1st stage for a constant sludge age, required for nitrogen conversion (low sludge age in 1st stage, due to carbon extraction for biogas production in digester) (Baumgartner et al., 2016).

As for anaerobic digestion, the extracted carbon in the form of sludge is stabilized under anaerobic conditions forming biogas and digested sludge. Digested sludge is further undergoing a dewatering process, most commonly by centrifugation resulting in reject water (sludge dewatering effluent, SDE) and a stabilized solid phase. The solid phase is usually passed on to waste incineration plants for further stabilization (inertization). At this stage SDE contains up to 15 - 20 % of the influent NH_4^+-N load. The concentration varies between 800 – 1500 mgN/L of NH_4^+-N. It has a very slowly biologically degradable COD, a concentration of suspended solids of around 200 mgN/L. SDE leaves the dewatering process with an approximate temperature of 25 - 30 °C. The longer the SDE is stored, the more temperature can decrease (Baumgartner et al., 2016).
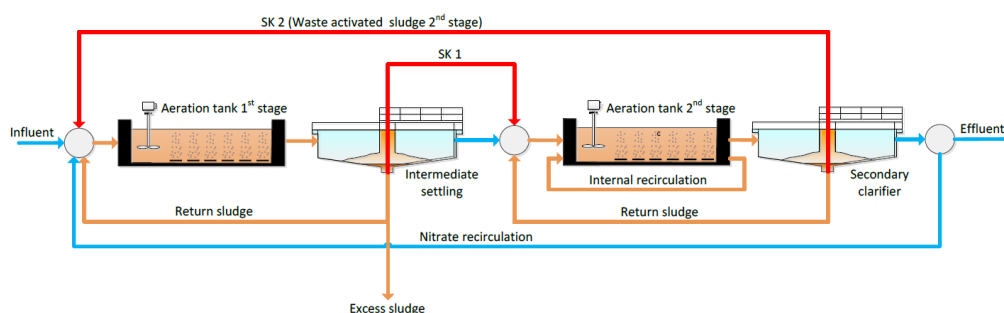
Figure 3: Flow scheme of an enhanced 2-stage WWTP (Baumgartner et al., 2016)

2.3 SDE Treatment

SDE treatment mainly targets an ammonium removal of the relatively high nitrogen load. It can be distinguished into side-stream and main-stream treatment but also varies between physical, chemical and biological treatment. Usually being introduced back in the main stream, this operation mode leads to some major drawbacks, considering the energy-consumption for the SDE treatment. Generally it can be said that side-stream treatment leads to a lower energy demand compared to main-stream processes. A cost reduction in SDE side-stream treatment include a reduction of the reactor volume and a reduction of the energy-demand for aeration (Baumgartner et al., 2016).
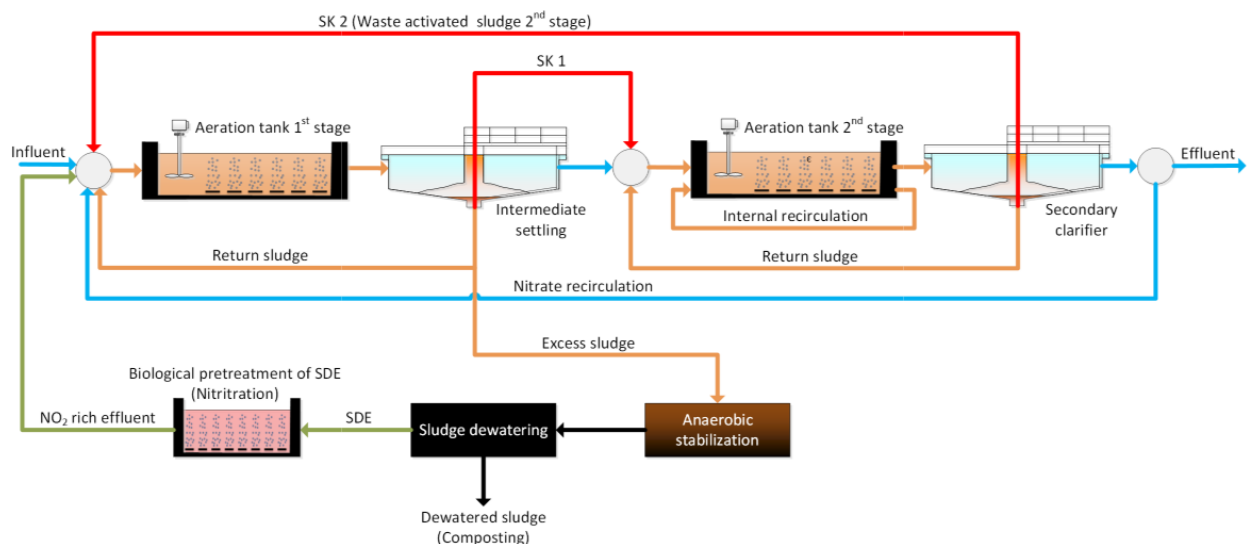
Figure 4: Flow scheme of an enhanced 2-stage WWTP with SDE side-stream treatment (Baumgartner et al., 2016)

Following drawbacks need to be considered when choosing SDE main-stream treatment only (Baumgartner et al., 2016):

- The increase of the high-loaded ammonium stream leads to a higher demand of aeration for nitrification in order to meet the threshold value of the nitrogen load in the effluent.
- Since the demand of aeration rises, the space for the activated sludge process increases equally, leading to a smaller anoxic volume for denitrification and hence to a

deterioration of the nitrogen removal. Furthermore a higher COD-respiration occurs, which leads to a lower readily biodegradable COD content for denitrification.

- Another major drawback represents the lower energy content in the surplus sludge when digested, due to the lower COD-content when SDE is introduced into the main-stream without pre-treatment.

Therefore a pre-treatment of SDE is recommended in order to achieve a reduction of the energy consumption for SDE treatment. The present thesis deals with the biological SDE side-stream treatment under aerobic conditions. SDE side-stream treatment leads to a lower ammonium load in the main-stream when reintroduced. This way an energy reduction can be achieved (Baumgartner et al., 2016).

2.3.1 Energy reduction potentials of SDE side-stream treatment

The nitrification process, described in Chapter 2.1.1, takes place under aerobic conditions. This means, that ammonium is oxidized to nitrite or nitrate under consumption of dissolved oxygen (DO). In denitrification nitrite and nitrate is reduced to nitrogen gas under anoxic conditions. Nitrite and nitrate hereby serve as the electron acceptors (instead of DO) for the oxidation of the organic carbon source. Hence the denitrification process reduces the demand of energy needed for the aeration (Baumgartner et al., 2016).

In Figure 5 it can be seen, that the conversion of ammonium to nitrogen gas is equal in terms of oxygen consumption, regardless of the biochemical path it undergoes. In other words, the oxygen consumption for the three different treatment options (nitrification/denitrification, nitritation/denitritation and anammox) is identical.

SDE pre-treatment option	O_2-consumption	O_2-yield	total
Nitrification/Denitrification	4.33 g O_2	2.86 g O_2	1.5 g O_2/g N_2-$N_{removed}$
Nitritation/Denitritation	3.74 g O_2	2.23 g O_2	1.5 g O_2/g N_2-$N_{removed}$
Anammox	1.93 g O_2	0.40 g O_2	1.5 g O_2/g N_2-$N_{removed}$

Figure 5: Total oxygen consumption for the conversion of 1 g NH_4-N through different nitrifying/denitrifying pathways (Baumgartner et al., 2016)

The only differences lies in the energy demand for aeration due to the different aeration factors the treatment options imply. The standard aeration efficiency (SAE) describes the amount of oxygen that can be transferred into clean water. The α-value is the ratio of SAE in wastewater to SAE in clean water. In main-stream the α-value is lower than in side-stream, due to a higher concentration of suspended solids. Hence a higher energy demand is required in order to achieve the required level of dissolved oxygen (DO). Another contributing factor is the amount of chemically bound oxygen (nitrite and nitrate), which is available for the nitrification process (Baumgartner et al., 2016).

The following Figure shows the different energy demands for aeration for the different WWTP configurations:

WWTP configuration	Energy from biogas	Energy for aeration	Δ
1-stage WWTP without SDE pre-treatment	13.8 kWh$_{el}$/PE/a	11.6 kWh/PE/a	+ 24.7 %
2-stage WWTP without SDE pre-treatment	18.4 kWh$_{el}$/PE/a	10.6 kWh/PE/a	+ 14.0 %
2-stage WWTP with SDE pre-treatment via nitrification	19.3 kWh$_{el}$/PE/a	9.3 kWh/PE/a	0.0 %
2-stage WWTP with SDE pre-treatment via nitritation	19.3 kWh$_{el}$/PE/a	9.6 kWh/PE/a	+ 3.2 %
2-stage WWTP with SDE pre-treatment via anammox	19.3 kWh$_{el}$/PE/a	9.7 kWh/PE/a	+ 4.3 %

Figure 6: Total energy demand for different treatment configurations (Baumgartner et al., 2016)

According to Baumgartner et al. (2016) the total energy consumption is the lowest for the configuration of a 2-stage WWTP with SDE pre-treatment via nitrification. As can be seen in Figure 6 the calculations include the energy demand for aeration and the energy won, through biogas utilization. The reason for this lies in the substitution of the oxygen demand for carbon removal in the first stage of a 2-stage WWTP through chemically bound oxygen (nitrite or nitrate). This way the energy demand for aeration is reduced in the aeration tank. Since nitrate contains a higher amount of chemically bound oxygen than nitrite, it is obvious that the SDE pre-treatment via nitrification represents the most efficient option (Baumgartner et al., 2016).

However, one drawback that this operation mode implies is the inhibition of NOB, due to the characteristics of the influent SDE. SDE, when directly sent to the pre-treatment tank, without being stored, has a rather elevated temperature of around 30 °C. Moreover it has a high ammonium concentration and a rather high pH-value of around (8 – 8.5). Based on

these conditions in SDE pre-treatment NOB inhibition occurs and nitritation instead of full nitrification takes place. More information upon NOB inhibition will follow in greater detail. One possible measure that can be taken in this case is dosing return sludge to the SDE pre-treatment tank in order to dilute the bulk liquid and thus prevent NOB inhibition due to a lower NH_4^+ concentration and a lower pH value in the system. This measure merely would imply a lower oxygen transfer rate caused by a higher concentration of suspended solids within the pretreatment tank. One result would be an increase for the aeration demand, making this operation mode less energetically favorable to operate. Therefore ammonium reduction through nitritation instead of nitratation is favored and desired since process is more stable and no dosage of return sludge is required (Baumgartner et al., 2016).

2.3.2   Alkalinity in SDE treatment

Alkalinity is the buffer capacity of water towards acids. In aqueous solutions alkalinity on the one hand depends on the equilibrium between dissolved CO_2 and CO_2 in the gaseous phase in water, which is described by the Henry-Dalton-Law. Henry-Dalton-Law depends on the partial pressure and Henry constant of CO_2. On the other hand it depends on the dissociation of dissolved CO_2 into hydrocarbonate (HCO_3^-) and carbonate (CO_3^{2-}). Both equilibriums have a strong impact upon the pH-value. In anaerobic digestion heterotrophic bacteria produce CO_2 which ends up as HCO_3^- in the SDE, based on the pH-value in SDE. HCO_3^- represents the buffer capacity for NH_4^+. When NH_4^+ is nitrified, 1 mol of buffer capacity is lost through the conversion of NH_4^+ to NO_2^- and 1 mol of acid is produced due to the formation of NO_2^-. In total 2 mol of buffer capacity is lost in this conversion process. For this reason only 50 - 60 % of NH_4^+ can be converted, since all of the available buffer capacity is consumed as soon as 50 % of NH_4^+ is converted. pH starts to drop let the process stop. SDE can therefore only be partially nitrited or nitrified, when no additional base is dosed (Svardal, 2005).

2.4   Control strategies for nitritation in SDE

Stopping the nitrification process at the first biological process step can be achieved through certain control strategies targeting an NOB inhibition or NOB wash-out out of the system and an enrichment of AOB. These strategies include the regulation of the system's

temperature, dissolved oxygen (DO) concentration, pH-value, sludge age, loading rate and the concentration of inhibitory substances within the system. These regulations aim to establish favorable conditions for AOB, while suppressing NOB, regarding their growth rate and their sensitivity towards inhibitory compounds, such as free ammonia (NH_3) and free nitrous acid (HNO_2) (Ge et al., 2015).

2.4.1 Temperature

Microorganisms increase their activity and their specific grow rate with increasing temperature. According to the overall literature research also nitrifying bacteria increase their activities with temperatures above 25 °C (Peng and Zhu, 2006). As reported by Brouwer et al. (1996) only at temperatures above 25 °C AOB are able to outcompete NOB, when regarding their specific growth rates only (Brouwer et al., 1996; Yoo et al., 1999). Camilla and Gunnel (2001) reported that the optimum temperature, using only pure cultures of both species was at 35 °C for AOB-Nitrosomonas and at 38 °C for NOB-Nitrobacter.

Temperature not only has effects on bacterial growth rates of AOB and NOB, but also influences the free ammonia (FA) and free nitrous acid (FNA) concentration, both of which have inhibitory effects on activity of nitrifying bacteria. Yamamoto et al. (2006) used partial nitration treatment for anaerobic digestion liquor of swine wastewater using swim-bed technology and reported successful nitration performance between 15 °C and 30 °C. Nitration however started to deteriorate at temperature below 15 °C due to decreasing effect of FNA inhibition on NOB with decreasing temperature. More on this topic is discussed in the following chapter.

2.4.2 Free ammonia (FA) and free nitrous acid (FNA) inhibition

FA and FNA depend on the temperature and pH-value within the system, as well as on the ammonia and nitrite levels, respectively. Determination of FA and FNA are calculated by Equation 7 and Equation 8, respectively (Ge et al., 2015). Details upon the calculation will follow in Chapter 6.

$$FNA = \frac{47 * NO_{2,eff}}{14 * (e^{\frac{-2300}{(273+T)}} * 10^{pH} + 1)}$$

<div align="right">Eq. 7</div>

$$FA = \frac{17 * NH_{4,eff} * 10^{pH}}{14 * (e^{\frac{6344}{(273+T)}} + 10^{pH})}$$

<div align="right">Eq. 8</div>

Both, free ammonia and free nitrous acid show inhibitory effects on AOB and NOB, while different threshold values for each of the substances are reported in the literature. Nonetheless, all of the found references agree, that FA and FNA show stronger inhibition on NOB than on AOB, since the threshold values for NOB are distinctly lower. Hence the regulation of the pH-value is commonly used for achieving nitrite accumulation according to a variety of literature sources found upon this topic (Cecen, 1996; Ge et al., 2015; Peng and Zhu, 2006; Peng et al., 2004). Generally, pH-value between 7.5 and 8.5 shows to keep partial nitrification stable (Abeling and Seyfried, 1992; Balmelle et al., 1992; Villaverde et al., 1997). However threshold values for NOB inhibition vary, e.g. Anthonisen et al. (1976) reported 0.1-1.0 mg N L^{-1} of FA for NOB inhibition, whereas Bae et al. (2001) reported values ranging from 0.1-4.0 mg N L^{-1}. FA thresholds for AOB inhibition are significantly higher. Anthonisen et al. (1976) reported threshold values ranging from 10-150 mg N L^{-1}, Nowak (1996) reported values ranging from 40-200 mg N L^{-1}, whereas according to Abeling and Seyfried (1992) ammonia oxidation is inhibited at FA 7mg N L^{-1}, and will almost stop at values of 20 mg N L^{-1}. However, all of the literature references found upon AOB and NOB inhibition seem to agree that AOB are far less sensitive to fluctuating pH-values than NOB.

For low pH-values below 7.5, also the exceedance of threshold FNA concentrations comes into effect for the inhibition of AOB and NOB (Sinha and Annachhatre, 2007). But also here, AOB inhibition plays a minor role with threshold values for AOB activity reduction of 50 % with FNA values of 0.42-1.72 mg N L^{-1}, while NOB inhibition through FNA already starts at concentrations of 0.011-0.07 mg N L^{-1} and reaches total inhibition at concentrations of 0.026-0.22 mg N L^{-1} (Zhou et al., 2011). The only condition for achieving FNA inhibition is, that nitrite must already have accumulated in the system in order to show inhibitive effects. However, FA and FNA inhibition are both reversible (Han et al., 2003), wherefore other

control factors must not be neglected. Furthermore, the state in which the biomass is present within the system need to be taken into account (flocculent sludge vs. biofilm). Inhibitory effects of the bacteria are different for flocculent sludge or biofilms, given to the mass transfer mechanisms they underlie (Piculell, 2016). Since both, temperature and the influent NH_4^+-N concentration are mainly kept constant, the regulation of the pH-value is adjusted by the NH_4^+ loading rate and it is used to control FA and FNA concentrations for the experiments in this thesis.

2.4.3 Sludge retention time (SRT)

As reported by Peng and Zhu (2006) the minimum doubling time of AOB ranges between 7 - 8 h while the doubling time for NOB is longer, between 10 - 13 h. Hence a NOB washout can be achieved by setting a SRT low enough, in order to maintain partial nitrification (nitritation). Full-scale experiences suggest a SRT of 1 day up to 2.5 days for nitrite accumulation (van Kempen et al., 2001). The adjustment of the sludge retention time (SRT) through the hydraulic retention time (HRT) is only feasible in suspended growth systems, since fixed-bed growth system and MBBR technology operate with SRTs uncoupled from HRTs.

2.5 Reactor configurations

Microorganisms in wastewater treatment plants grow spontaneously, but their growth can be controlled by certain operation modes such as hydraulic retention time (HRT), sludge retention time (SRT), aeration and load (Piculell, 2016). There are different strategies to maintain a certain amount and diversity of bacteria within the biomass of a system (adjustment of the sludge age). Biological wastewater treatment technologies can be categorized into attached and suspended bacterial growth systems (Piculell, 2016).

2.5.1 Suspended growth system

In suspended growth systems, or also activated sludge system, microorganisms grow in flocks, which are moving around freely within the bulk liquid. This approach applies sludge

sedimentation and recirculation in order to keep the biomass in the system and this way adjust a certain sludge age. Activated sludge systems are considered to be more flexible and require less maintenance, but they are rather sensitive to fluctuating flow rates, due to biomass wash-out and to toxic environmental conditions (Henze et al., 2002; Jönsson, 2001).

2.5.2 Attached growth system

Attached growth-, or also fixed-film growth systems, applies trickling filters, which act like a support material, where microorganisms can grow on. This technology is considered to be more compact, in terms of the required space, but less sensitive to harmful environmental impacts. A clear drawback this technology implies is a relatively high rate of support material clogging (Henze et al., 2002).

2.5.3 Moving Bed Biofilm Reactor

MBBR technology combines, to a certain extent, the benefits of both technologies and at the same time minimizes some of their drawbacks. MBBR technology applies plastic carrier elements on whose surface an active biofilm can grow. A biofilm can be described as an agglomeration of several species of microorganisms attached to a solid surface existing in humid or aqueous environments. The production of their own extracellular polymeric substances (EPS) allows the bacteria to form a protective layer, where adhesive forces enable them to attach on all kinds of surfaces. This way bacteria within this biofilm are less susceptible to toxic substances or dehydration and permit the establishment of different microbial clusters and hence a variety of applications for engineering challenges (Piculell, 2016; R Robertson et al., 2015). In MBBR the biofilm is able to grow in a more or less sheltered environment, provided by the voids and cavities of the particularly shaped carriers. The shape of the carries moreover provide a large surface area, where a biofilm can grow (Ødegaard, 1999). By mechanical mixing or aeration the carriers are kept in constant movement, enhancing the substrate availability and preventing carrier clogging, due to mechanical shear forces among the carriers themselves. By this means, the treatment capacity of MBBR compared to the two conventional technologies is significantly higher (Ødegaard, 1999). Since the carriers are kept in the system by retention sieves also the

biomass is retained (McQuarrie and Boltz, 2011), meaning that the sludge retention time (SRT) of MBBR is not adjusted through the hydraulic retention time (HRT). This allows the system to work with sludge retention times, uncoupled of the NH_4^+ loading rate. The sludge age is therefore much higher and enables the growth of slow-growing bacteria, which otherwise would be washed out (Christensson et al., 2013).

2.5.3.1   Substrate transport mechanism

A major difference between activated sludge and fixed-film systems is the substrate availability, given by the diffusion rate through the biofilm, since it is clearly the major substrate transport mechanism in biofilm systems. Diffusion rates of all kinds of substrates depend on the concentration gradients between the bulk liquid and the biofilm. Since bacterial activity relies on substrate supply, the diffusion rate through the biofilm is a limiting factor for bacterial metabolism and further for the efficiency of MBBR technology (Boltz and Daigger, 2010).

As for oxygen diffusion, a crucial substrate for nitrification and nitritation, an anaerobic zone can occur at the innermost layer of the biofilm, followed by an aerobic layer with increasing DO concentration towards the bulk liquid. These different layers and the different environments that arise for the microorganisms may result in several different microbial niches and may enable the co-existence of different bacteria. While aerobic bacteria will naturally grow in the top layers, anoxic and anaerobic bacteria can establish themselves more easily in the inner layers. Nonetheless not only oxygen limitation will occur, but also substrate limitation, caused by various substrate diffusion rates, which further results in competing microorganisms longing for substrate and hence creating even more microbial niches for co-existing bacteria (Gieseke et al., 2003). At the same time a limiting diffusion rate of other compounds in biofilms may act like a protective layer for the inner layers, making the MBBR more resistant to toxic disturbances, compared to suspended growth systems (Piculell, 2016).

2.6   N$_2$O emission in WWTP

A significant amount of nitrous oxide (N$_2$O) can be emitted during biological conversion steps of nitrogen. As a highly-potent greenhouse gas (being 298 times more effective than CO$_2$) the anthropogenic emission of N$_2$O substantially contributes to global warming. The estimated half-life of N$_2$O is about 120 years which makes it even last for centuries in the atmosphere. Its atmospheric accumulation is therefore even more alarming. Due to increasing N$_2$O emission over time, its controlled emission has become a crucial part of a sustainable operation of biological wastewater treatment plants (Kampschreur et al., 2009; Kong et al., 2013).

According to Kampschreur et al., (2009) N$_2$O emission occurs particularly in aerated zones of WWTP. However it remains unclear if whether in nitrifying or denitrifying microorganisms are responsible for its production. Its increased emission in aerated zones can be attributed the faster stripping of dissolved N$_2$O in aerated zones than in calm anoxic zones. Nevertheless it does not necessarily have to mean that the production of N$_2$O can be attributed to autotrophic microorganisms only. Dissolved N$_2$O, which was priorly produced in the in denitrification stage, can later on be emitted in the gaseous phase, when being stripped in an aerated nitrification stage. N$_2$O has a relatively high solubility in water. The Henry-coefficient is 0.024 M/atm, while the one of oxygen only amounts to 0.0013 M/atm. N$_2$O emission can therefore also be emitted through the effluent pathway ending up in the rivers or estuaries. Increasing solubility with decreasing temperatures can therefore also lead to an increased amount of N$_2$O being discharged in the dissolved phase rather than being stripped out in the gaseous phase (Kampschreur et al., 2009; Kong et al., 2013).
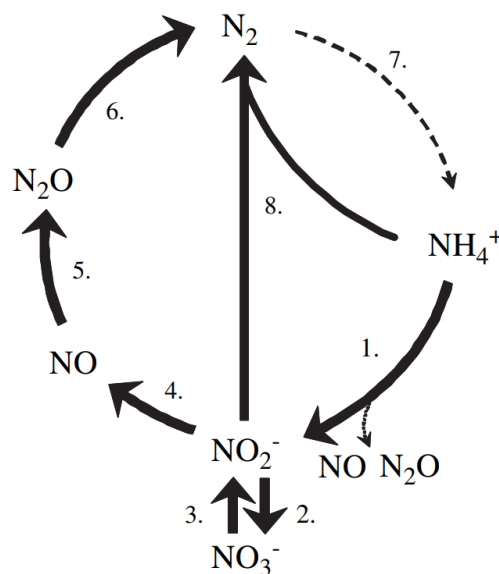
Figure 7: Biological nitrogen conversions (Kampschreur et al., 2009)

Figure 7 shows a simplified version of the biological nitrogen cycle with its conversion products and intermediates (Kampschreur et al., 2009):

(1) aerobic ammonia oxidation (autotrophic and heterotrophic AOB)

(2) aerobic nitrite oxidation (NOB)

(3) nitrate reduction to nitrite (by denitrifiers, DEN)

(4) nitrite reduction to nitric oxide (AOB and DEN)

(5) nitric oxide reduction to nitrous oxide (AOB and DEN)

(6) nitrous oxide reduction to dinitrogen gas (DEN)

(7) nitrogen fixation (not relevant in most WWTPs)

(8) ammonium oxidation with nitrite to dinitrogen gas (Anammox).

Complete nitrification comprises step 1 and 2, complete denitrification step 3–6 (Kampschreur et al., 2009).

2.6.1 Influencing factors for N_2O emission in SDE treatment

Known operational parameters to trigger N_2O emission are: (i) low DO concentration in both nitrification and denitrification stage, (ii) increased nitrite levels in both stages and (iii) a low COD/N ratio in denitrification stage. (Kampschreur et al., 2009). While (iii) is of minor

importance for SDE side-stream treatment, (ii) is the probably the main reason for N_2O emissions in nitrifying process like in SDE side-stream treatment.

During nitrification, when oxygen limiting conditions arise, AOB use NO_2^- as the terminal electron acceptor. This way precious oxygen is saved for the reaction of ammonia to hydroxylamine (NH_2OH). According to Goreau et al., (1980) N_2O production can correspond to 10 % of the nitrogen load at a DO level below 1 mg/L in nitrification.

High nitrite levels promote nitrite reduction to N_2O during nitrification, which is performed by AOB as a by-product, as can be seen in Figure 7 (Colliver and Stephenson, 2000). According to Tallec et al., (2006) and artificial nitrite pulse of 10 mgN/L provoked a 4 to 8-fold N_2O emission during nitrification, depending on the DO concentration. According to (Castro-Barros et al., 2015) a 5-fold N_2O emission was observed in a nitrifying lab-scale reactor fed with low strength ammonium wastewater when a nitrite pulse of 50 mgN/L was added. After nitrite had oxidized, N_2O emission went back to the level before the nitrite pulse.

Operation condition in SDE side-stream treatment over nitritation like high ammonium and nitrite levels, low COD, high temperature and fluctuating pH-value can lead to a higher N_2O production, compared to common nitrification in WWTP (Baumgartner and Parravicini, 2018). Rodriguez-Caballero and Pijuan (2013) observed significantly lower N_2O emissions from nitrification processes ($EF_{N20-N/N\ oxidized}$ of 0.54 %) compared to those from nitritation ($EF_{N20-N/N\ oxidized}$ of 1.22 %). N_2O emission factors of full-scale partial nitritation system among to 1.7 – 6.6 % of the influent ammonia load and 3.4 – 11.2 % of the oxidized ammonia load (Desloover et al., 2011; Kampschreur et al., 2008; Pijuan et al., 2013).

3   Material and Methods

3.1   Reactor set-up and characteristics

Lab-scale experiences were performed on 4 single reactors (R1 - R4). For all reactors, cylindrical-shaped vessels with an effective working volume of 3L were used. The vessels of reactor 1 (R1) and reactor 2 (R2) have an inner-diameter of 14 cm and a height of 35 cm. Reactor 3 (R3) and Reactor 4 (R4) have the same inner-diameter with a height of 60 cm. R1 and R2 were inoculated with seed sludge composed of 500 mL flocculent activated sludge from the second stage of a municipal WWTP, which showed a high nitritation performance. 2.5 L of tap water was added to this, resulting in 3L working volume for each reactor. Through an aquarium diffuser stone attached at the bottom of both reactors the system is supplied with sufficient oxygen needed for the given aerobic biological process. By adjusting the influent air flow rate it was made sure, that dissolved oxygen was in excess for the whole investigation period. Moreover the turbulences caused by the emitting air bubbles provided the required mixing within the system. The characteristics of every single reactor are shown in Table 1.
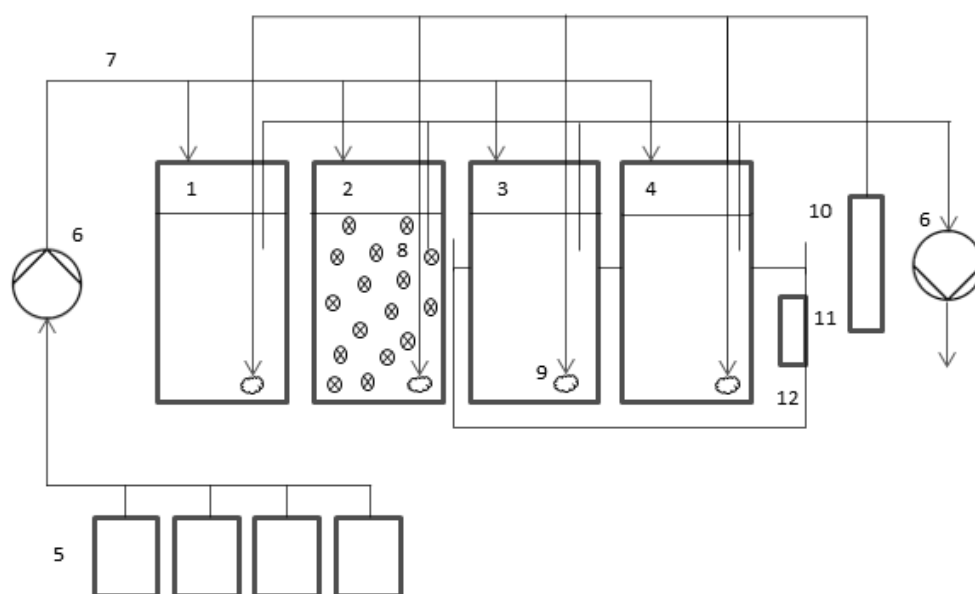
Figure 8: Schematic diagram of experimental set-up

Figure 8 shows the schematic diagram of the whole set-up with following elements: (1) R1; (2) R2; (3) R3; (4); R4; (5) influent feed tanks for R1 – R4; (6) peristaltic pump for feeding and withdrawal, while withdrawal is only required on weekends and for certain phases, as will follow in Chapter 3.2.1; (7) influent feeding tubes; (8) carrier media; (9) air stone diffuser; (10) pressurized air tank; (11) thermostat; (12) water bath.

Table 1: Reactor configurations of R1 – R4

name	configuration	characteristics
R1	Continuously Stirred Tank Reactor (CSTR)	temperature not regulated/ ambient temperature
R2	Moving Bed Biofilm Reactor (MBBR)	temperature not regulated / ambient temperature
R3 / R4	Continuously Stirred Tank Reactor (CSTR)	temperature regulated (25 °C – 15 °C)

R2 uses MBBR technology for the biological nitrogen removal. For MBBR disk shaped carrier media (Type K5) manufactured by AnoxKaldnes^{TM} are used. A picture of the carrier elements can be seen in Figure 9. The nominal diameter of the carriers is 25 mm with a thickness between 3.5 to 4 mm with an approximate surface area for biofilm growth of 800 m^2/m^3 ± 1%. It is composed of high-density polyethylene with a density of 0.95 kg/dm^3. Initially seeded with 150 carriers, on process day 18 another 150 carriers were added, resulting in a total amount of 300 carriers for 3 L working volume. With a number of 331,000 carriers per m^3, given by the provider, the effective surface area for the biofilm growth of R2 can be calculated as following:

$$\textbf{effective surface area} = \frac{\textbf{1 m}^3}{\textbf{311,000 carriers}} * \textbf{300 carriers} * \textbf{800}\frac{\textbf{m}^2}{\textbf{m}^3} = \textbf{0.725 m}^2 \qquad \text{Eq. 9}$$
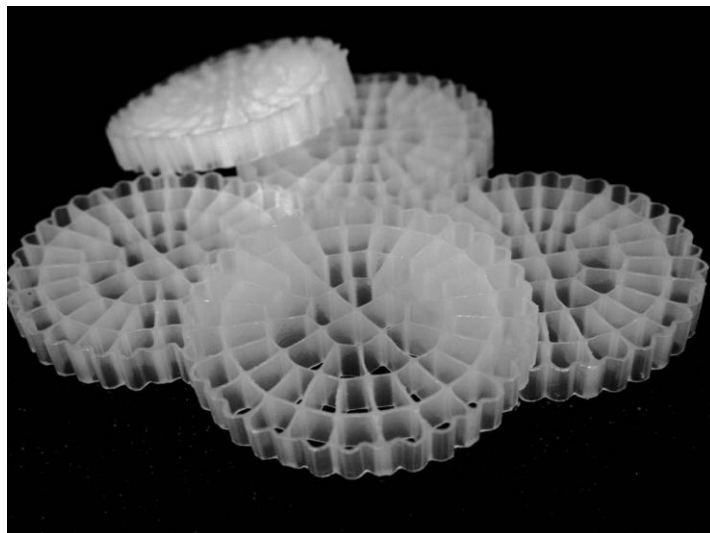
Figure 9: Type K5 carrier media for MBBR by AnoxKaldnes^{TM}

R3 and R4 started up on process day 61. The aim of R3 and R4 is to study the influence of the temperature upon the given biological systems, especially regarding nitritation performance. The implementation of R3 and R4 is equal to R1, applying a suspended growth system (CSTR). For inoculation of R3 and R4 effluent of R1 was used, which by that time, showed a high nitrite accumulation ratio. Both reactors were immersed in a water bath, which served as a temperature control system in order to control and set the desired temperature. The water bath was supplied by cool tap water, whereas a thermostat is used to adjust the desired temperature within the water bath and therefore regulates the temperature in both reactors. Two reactors, instead of one were used for this purpose in order to obtain representative results (induplicate), in order to confirm the reproducibility of the experimental results.

The feed consists of sludge dewatering effluent (SDE), which was supplied by a municipal wastewater treatment plant with a population equivalent of 165.000 population. The anaerobically digested sludge of this WWTP is dewatered by a centrifuge using polymers, resulting in reject water (SDE) and a solid residual. Characteristic parameters of the influent SDE throughout the whole investigation period is shown in Table 2.

Table 2: SDE characteristics over process time

	NH_4^+-N [mgN/L]	COD [mgN/L]	COD mf [mgN/L]	BOD [mgN/L]	Suspended solids [mgN/L]
SDE	958 ± 157 (n=18)	260 ± 114 (n=18)	201 ± 84 (n=18)	59 (n=1)	56 ± 149 (n=18)

3.2   Operation mode

The overall goal of the study is to find out the suitable operating conditions for achieving a stable nitritation performance in SDE side-stream treatment for different kinds of biological systems. The aim is to slowly increase the ammonium loading rate (NH_4^+-loading rate), while meeting an ammonium removal degree (NH_4^+-removal degree) of about 50 - 60 %, without causing AOB inhibition due to high FA concentrations. AOB inhibition causes an overloading and NH_4^+-removal degree falls below 50 %. The setting of the appropriate NH_4^+-loading rate follows the pH-value of the system. A low pH-value indicates a low NH_4^+-N concentration in the reactor. For this reason NH_4^+-loading rate can be increased. A high pH-value on other hand indicates a high NH_4^+-N concentration and NH_4^+-loading rate needs to be reduced, in order to avoid an overloading and to meet the NH_4^+-removal degree of 50 %. The maximum NH_4^+- loading rate under the given conditions is to be determined for each of the systems. Since the NH_4^+-N concentration in the influent remained relatively stable at 850 - 1050 mgN/L, NH_4^+-loading rate was increased by increasing the influent flow rate. An increase of the NH_4^+-loading rate leads to an increase of the pH-value. The influent pH-value amounts to > 8.5 approximately, although no regular measurements were conducted. Nevertheless, since the NH_4^+-N concentration in the influent is considered to be stable, the pH-value in the feed can be assumed to be stable as well. However, for the pH-value in nitrifying systems also other factors play an important role, as mentioned above. According to the chemical equation for the nitritation process H^+-ions are formed and released, which leads to a drop of the pH-value. The nitratation process on the other hand does not influence the pH-value significantly.

At the same time a high nitrite accumulation should be achieved and the operating conditions for maintaining high nitritation need to be studied. Nitritation performance can be measured through the calculation of the nitrite accumulation ratio (NAR). More detailed information upon NAR can be found in Chapter 3.6 for Calculations. For a high nitritation performance NAR should be close to 1. Particular focus should be put on the influencing factors or operating conditions when nitrite accumulation decreases. Decreasing nitrite accumulation occurs when NOB activity becomes higher. The required actions that need to be taken in order to inhibit NOB activity are to be determined. Control strategies for

achieving and maintaining a high NAR focus on the regulation of the sludge retention time (SRT) and inhibitive FA and FNA concentrations through NH_4^+-N and NO_2^--N concentrations, coupled with pH-value and temperature of the system. Due to the given conditions in SDE treatment (high ammonium concentration, high temperature) NOB show slower growth rates than AOB. The idea is to keep SRT low in order to achieve a NOB-washout and an AOB accumulation within the system. For NOB inhibition through a inhibitive FA levels a high pH-value and a high NH_4^+-N concentration in the reactor is desired. Both influencing factors (low SRT, high FA levels) can be achieved by choosing a high NH_4^+ loading rate. However these parameters are crucial especially for a continuously-stirred-tank-reactor (CSTR). For MBBR SRT is cannot effectively be controlled. For this reason other influencing factors, like the characteristics of the biofilm need to be evaluated. Studies upon R3 and R4 show the influence of the temperature upon the overall systems performance, in terms of ammonium removal degree, maximum loading rate and the nitrite accumulation ratio.

3.2.1 Operation modes for R1 and R2

For R1 and R2 investigations were performed throughout a period of 325 process days, divided into 5 overall phases (phase A - E). These phases especially consider the differences of the feeding mode, that has been applied and the method for the adjustment of the solid retention time.

Table 3: Reactor characteristics of R1 and R2

phase	process day	characteristics
phase A	0 – 32	start-up phase, activation and growth-phase of microorganisms, discontinuous withdrawal
phase B	32 – 50	continuous loading with diluted feed, continuous withdrawal through tubes
phase C	50 – 121	continuous loading with undiluted feed, continuous withdrawal through tubes
phase D	121 – 157	continuous loading with undiluted feed, discontinuous withdrawal
phase E	157 – 320	prevention of biofilm build-up on the reactor walls

Phase A: For the initial start-up phase of the system, discontinuous feeding is applied, since the peristaltic pump was not able to apply a feeding rate low enough, in order to avoid a system overload due to AOB inhibition. The initial discontinuous feeding procedure is done as following: 1L of the reactor volume was withdrawn and put aside, while the desired amount of SDE was added. Afterwards the withdrawn reactor content was used to refill the reactor up to the initial 3L. The remaining liquid was disposed. A slow increase in the feed volume was applied day by day, until it was possible to apply a continuous feed by using a peristaltic pump. Before the feeding procedure was applied, the evaporated reactor content had to be compensated with tap water by filling up the reactor up to the initial working volume of 3L. Afterwards liquid samples are taken. By this means it can be ensured, that the amount of measured compounds are not concentrating within the liquid phase, due to water evaporation.

Phase B: In phase B the system is fed continuously through a pump. Initially diluted feed is used, since the system was yet not able to handle undiluted feed. Diluted feed consists of undiluted SDE and effluent of the reactor. Effluent is used for dilution instead of water in order to maintain a high NH_4^+-N concentration within the system, since effluent still contains about 50-60 % of the influent concentration of NH_4^+-N. By maintaining a high NH_4^+-N concentration also FA levels can be kept high. For the feeding procedure a peristaltic pump is feeding the reactors with SDE through tubes from the feed tank into the reactor. The amount of feed over time is determined gravimetrically through a scale, assuming the density of the feed to be equal to the density of water (approximately 1000 kg/dm^3). In the beginning some difficulties in finding the adequate setting for the pump occurred, in order to set an appropriate volumetric flow rate. Since the NH_4^+-N concentration of the feed was more or less constant, the only way to increase the NH_4^+-loading rate was to increase the flow rate. Flow rate can be adjusted through the rotation speed of the pump or through the size of the supply tubes. The outcome of this phase was a rather unstable loading rate, due to frequent system overload and the required recover phase afterwards. This also implies high fluctuations in pH-value and hydraulic retention time. After some time, the ideal method for setting the flow rate was found. The setting of the pump was kept constant, while only the inside diameter of the tubes were adjusted, in order to set desired flow rates. This way, after a certain time of high fluctuations of the NH_4^+-loading rate in the start-up phase, a more or less stable operating mode could be found.

Phase C: phase C applies continuous loading and withdrawal with undiluted feed. This operation mode led to a slow, but constant accumulation of sludge within the system, since a high amount of suspended solids were not withdrawn, due to thin tubes. SRT was higher than HRT.

Phase D: The system is loaded continuously with undiluted SDE and is manually withdrawn on a daily basis (except for weekends and holidays). Hereby the sludge retention time can be adjusted through the hydraulic retention time.

Phase E: The feeding mode and sludge withdrawal of phase D remains the same for phase E. The only difference is that the walls and the bottom of the reactors were cleaned on a daily basis by a rubber spatula, in order to avoid biofilm build-up upon the reactor walls. More details upon this can be found in the description for operation mode of R3 and R4.

3.2.2   Operation modes for R3 and R4

The studies throughout the period of 265 process day are divided into 4 phases (phase A, C, D, E). All phases apply the same feeding mode like R1 and R2. Phase B, however is skipped for R3 and R4 since, continuous feeding started directly with undiluted feed instead of a feed/effluent dilution.

Table 4: Reactor characteristics of R3 and R4

phase	process day	characteristics
Phase A	0 – 21	start-up phase, activation and growth-phase of microorganisms discontinuous withdrawal
Phase C	21 – 61	continuous loading with undiluted feed, continuous withdrawal through tubes
Phase D	61 – 97	continuous loading with undiluted feed, discontinuous withdrawal
Phase E	97 – 265	prevention of biofilm build-up on the reactor walls

Phase E: It has been noted, that especially in R3 and R4 a significant amount of biofilm established on the reactor walls and bottom. It was unnoticed up to process day 97 (process day 157 for R1 and R2), since both reactors were immersed in a water bath for the

temperature control and biofilm formation was not visible from the outside. The biofilm was assumed to considerably contribute to the ammonium conversion performance of both reactors and to increase the sludge retention time. For this reason the walls of all reactors were cleaned from that day on, on a daily basis in order to avoid a biofilm build-up. Even though in full scale suspended growth systems biofilm on the reactor wall also contributes to the performance of the system, it has a negligible influence compared to the ratio between wall surface and reactor volume in laboratory scale and in full scale.

3.3 Measurement of the oxygen uptake rate (OUR)

Studies upon oxygen uptake rate show the development of NOB and AOB activities through the whole period of the investigation. Moreover it shows the distribution of the bacteria between the bulk liquid and the carrier biofilm for R2. The different oxygen consumption between AOB and NOB can be revealed through AOB inhibition with ATH.

For OUR measurement, a sample of the reactor content (sludge) is poured into a small measurement vessel. A cylindrically-shaped cap seals the vessel without allowing the liquid content to leak or air bubbles to remain in the cell. OUR measurement can require the addition of substances. A small hole in the cap allows the injection of these substances through an injection syringe. Also the oxygen sensor unit is placed in a hole in the cap with a diameter of approximately 1 cm. Oxygen consumption is measured through a multi-meter with an LDO sensor for dissolved oxygen measurement. The multi-meter is connected to a computer. A special program records the decreasing dissolved oxygen concentration over a time. A magnetic stirrer and a magnetic rod within the measurement vessel assure perfect mixing. A collecting vessel keeps all of the surplus liquid and acts as a water bath, which keeps the temperature within the measurement cell constant, as the overflowing sludge has the same temperature as the sludge within the measurement vessel.
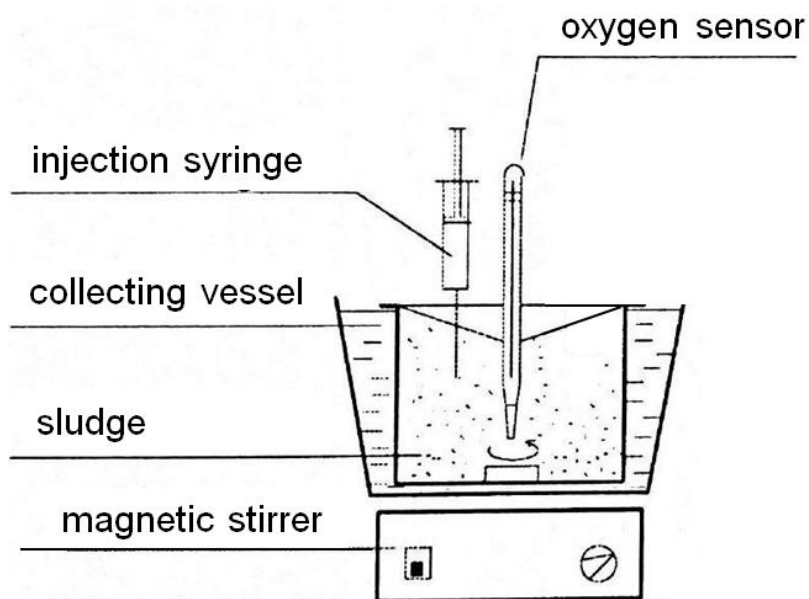
Figure 10: Set-up for OUR determination

Required substances:

- Sodium hydrogen carbonate (NaHCO₃):

  $NaHCO_3$ is required for stabilization of pH-value. During nitritation pH-values decreases. Through the addition of $NaHCO_3$, alkalinity limitations do no longer interfere the nitrification process of AOB and NOB and pH-value is kept stable.

  For 500 mL reactor content, 0.6 mg $NaHCO_3$ is added. Molecular weight of $NaHCO_3$ amounts to 84.01 g/mol.

- Allylthiourea (ATH):

  ATH solution consists of 1 g ATH/L. 1 mL is injected through the syringe and about 1 min is needed until OUR determination can be started. ATH shows an inhibitive effect upon AOB. This way OUR for remaining heterotrophic bacteria and OUR for NOB is determined. OUR for heterotrophic bacteria can however be neglected in SDE treatment, since COD concentration is negligibly low.

- Ammonium chloride (NH₄Cl):

  NH_4Cl solution consists of 10 g NH_4-N/L. With a dosage of NH_4Cl the maximum OUR for nitrifying bacteria is measured. Since the addition of $NaHCO_3$ already enables a complete nitrification the OUR with or without the addition of $NaHCO_3$ is assumed to not differ significantly. 1 mL of NH_4Cl is added through the injection syringe.

Oxygen uptake rate provides information about the bacterial activity and the ammonium loading rate capacity for each reactor, as far as temperature is the same in the reactor and during measurement. Moreover it reveals the sludge distribution between bulk liquid and biofilm of the carrier for R2. For OUR determination 500 mL is withdrawn from each of the 4 reactors. 0.6 mg of $NaHCO_3$ is added and well stirred. pH-value is noted and compared to the pH-value after measuring. No significant change in pH-value should occur. In order to saturate the sludge with oxygen, the sludge is shaken in a 1 L flask. Afterwards it is poured into the measurement vessel. Foam on the surface is carefully removed. The cap, with the oxygen sensor attached, is gently put on top of the vessel until it is sealed. The recording program is immediately started when LDO sensor immerses the liquid. Decreasing dissolved oxygen concentration over time is recorded and converted into a file. The oxygen sensor also records changes in temperature if relevant. R1 and R2 are operated under ambient temperature, whereas R3 and R4 require focus on thermostatic conditions during OUR measurement. Hence the collecting vessel is additionally filled up with water from the water bath where R3 and R4 are immersed in. More or less steady temperatures can this way be ensured. The calculation for OUR is shown in Chapter 5. OUR is expressed in mg/(L*h).

Up to process day 276, 12 OUR measurements were performed for R1. From process day 276, another 4 OUR measurement additionally determine OUR with addition of NH_4Cl and ATH. For R2 two OUR measurements were performed on each measurement day. First measurement was carried out with bulk liquid of the reactor content only, while the second measurement also includes the carrier media. Since the measurement vessel contains an effective volume of 300 mL, 30 carriers were used for OUR determination. This amount represents the same degree of carrier media filling like in the main reactor of R2. Up to process day 142 however, the oxygen saturation procedure was carried out with the carrier media inside of the 1 L flask when the sludge was shaken. This led to a high degree of biofilm abrasion. All of the biofilm ended up as flocculent sludge in the bulk liquid. Moreover the chronological order of the measurement was different. OUR of R2 with carrier media was determined first and OUR R2 without carrier media after. For this reason, up to process day 142, OUR of R2 without carrier media was comparatively high. By process day 151, sludge was no longer shaken with carriers inside of the flask. More representative results were obtained regarding the biofilm distribution. OUR determination of R2 with ATH was only

performed once on process day 276. For R3 and R4 OUR measurement was performed 4 times. All 4 measurements were performed with addition of NH_4Cl and ATH.

3.4 Evaluation of N_2O emission

For sampling a 20 mL glass vial was hermetically sealed with a butyl septum and fixed with an aluminum ring. The glass vial was then evacuated for 1 min to -70 kPa. The sample contained 10 mL of sampled gas and was introduced into the glass vial through an injection syringe. For each reactor two samples were taken (sample A and sample B). A mean value of both values is created and represents the concentration of the measured compounds. If CO_2 was 0, it was assumed that the measurement was not successful and air had entered the glass vial. The measurement value in this case was eliminated. The evaluation of the influent air flow rate was performed through volumetric water displacement over time. Therefore the reactor was hermetically sealed with a fitting cap. The cap has two tubes on its top. The first tube allows the introduction of the inflowing air stream into the reactor, while at the same time the inflowing air stream displaced gas can leave the reactor through the second tube. A measuring cylinder is immersed upside down into a cylindrically-shaped water vessel. The bottom of this cylinder is connected to a tube. The tube is connected to the outflowing tube of the reactor cap with the effluent air stream. Through monitoring the volumetric water displacement of the effluent air stream over time the air flow rate is determined. Also the gas sample was taken from the effluent gas stream of the reactor's cap.

3.5 Analyses

Liquid samples are taken every second day (usually Monday, Wednesday and Friday) from process day 12 - 199 and twice a week from process day 200 – 325. Since all of the reactors are perfectly mixed, the samples for the effluent concentrations are taken from the reactor directly. Measurement values include the influent and effluent NH_4^+-N concentrations, effluent NO_X-N concentration (sum of NO_3^--N and NO_2^--N) and the effluent NO_2^--N concentration.

For the influent NH_4^+-N one sample out of a well-mixed tank is taken. For this reason the influent NH_4^+-N concentration are equal for all four reactors and considered to be stable for the time the reactors are fed up to the point where the tanks are empty. However between process day 82 – 89 a sample of the influent NH_4^+-N concentration of the feeding tank was taken before and after the tank was refilled. The results show that, the influent NH_4^+-N concentration did not decrease over time within the feeding tank. For this reason ammonia escaping in form of gas, due to elevated room temperature in the summer period can be neglected. The dissociation of ammonium and ammonia follow a chemical equilibrium which is determined by temperature and pH-value.

When taking samples for soluble parameters from the reactor, the aeration is switched off for a short time of approximately 1 min, in order to let particulate matter settle down. Samples were centrifuged by a SIGMA 3-16L centrifuge at 4200 rpm for 4 min, in order to settle the residual particulate matter at the bottom of the sample tube. The analyses were performed by an auto-analyser (SKALAR, Netherlands), applying DIN EN ISO 11732 for NH_4^+-N concentration, DIN EN ISO 13395 for NO_2^-- N and NO_3^--N. Additionally analysis of the influent SDE contain COD, COD mf content, total suspended solids and BOD, which are performed according to DIN 38409-43, DIN ISO 15705, DIN38409-2, and DIN EN 1899-1, respectively. Gas samples were measured via GC-MS (Thermo Fisher Scientific, USA). Gas analyses include N_2O and CO_2 content.

On a daily basis (Monday - Friday) following parameters were measured or determined:

- Temperature and pH-value were measured with HQ 40d multi-meter (Hach, Germany) with a Hach IntelliCAL^{TM} PHC101 electrode. The electrode was calibrated biweekly.
- Dissolved oxygen concentration (DO) was measured by the same multi-meter with an IntelliCAL^{TM} Standard LDO sensor. It was made sure, that DO did not fall below 2 mgN/L, in order to guarantee a sufficient DO supply.
- Amount of water added to the reactor was noted, before taking liquid samples, in order to compensate the amount of water lost due to evaporation.
- If required, the amount of HCl (5 mol/L) added, was noted, in order to adjust pH-value in case of a system overloading. This was the case when loading rate and the pH-value were so high, that threshold values for AOB inhibition were exceeded.

3.6 Calculations

- **Ammonium loading rate (NH$_4^+$-loading rate):**

$$load_{NH4,inf} = \dot{V}_{inf} * NH_{4,inf}^+ - N \qquad \text{Eq. 10}$$

Ammonium loading rate provides information upon the amount of ammonium in mg N/d that enters the system. Ammonium loading rate is calculated on a daily basis. For the influent NH$_4^+$-N concentration ($NH_{4,inf}^+ - N$) one sample is taken, which is representative for all 4 reactors. Everytime the feed tank is refilled a new sample is taken. The influent volumetric flow rate ($\dot{V}_{inf}$) is determined gravimetrically. The weight of full feed tank and the empty feed tank is determined. A steady performance of the influent peristaltic pump is presumed. In case of a clogging an evenly distributed flow rate over the whole time of the feeding procedure is assumed, even though it does not correspond to the actual flow rate. One process day begins at 9 am and lasts 24 hours until the following day.

- **Effluent NO$_x$ –N concentration:**

$$NO_{x,eff} - N = NO_{2,eff}^- - N + NO_{3,eff}^- - N \qquad \text{Eq. 11}$$

- **Nitrite accumulation ratio (NAR):**

$$NAR = \frac{NO_{2,eff}^- - N}{NO_{x,eff} - N} \qquad \text{Eq. 12}$$

Nitrite accumulation ratio provides information upon the amount of nitrite being formed compared to the amount of ammonium that has been converted. It allows quantification of the AOB-activity. It is a ratio and ranges between 0 and 1, while 1 means a high nitrite accumulation and therefore no NOB activity occurrence. A value of 0 means full nitrification takes place and all of the NO$_2^-$-N is further converted to NO$_3^-$-N by NOB.

- **Ammonium removal degree:**

$$ammonium\ removal\ degree = \left(1 - \frac{NH_{4,eff}^{+} - N}{NH_{4,inf}^{+} - N}\right) * 100 \qquad \text{Eq. 13}$$

Ammonia removal degree reveals information about the NH_4^+-N removal performance of the reactors. It is calculated as one minus the ratio between the measured effluent NH_4^+-N concentration on one day and the influent NH_4^+-N concentration the day before. Thus, ammonia removal degree is only calculated for the day before liquid samples are taken. The exact measured value of the concentration of NH_4^+-N in the system represents the NH_4^+-N removal performance of the reactor within one day. It is a ratio and expressed as an percentage value. 100 % means a total conversion of NH_4^+-N while 0 % would mean that no conversion takes place. Due to alkalinity limitations in SDE treatment, however it usually does not exceed 65 %. A removal degree below 50 % indicates a system overloading of feed, which causes lower removal performances due to FA inhibition.

- **Free nitrous acid (FNA) concentration:**

$$HNO_2 \rightleftharpoons H^+ + NO_2^{-} \qquad \text{Eq. 14}$$

$$FNA = \frac{47 * NO_{2,eff}^{-} - N}{14 * (e^{\frac{-2300}{(273+T)}} * 10^{pH} + 1)} \qquad \text{Eq. 15}$$

Free nitrous acid follows a dissociation equilibrium in aqueous solutions, as described in Eq. 14. The calculation of the FNA concentration allows the determination of whether inhibitive threshold values for AOB or NOB are reached or not. It is calculated with the effluent NO_2^--N concentration, temperature and pH-value measured on the same day. Hence only when liquid samples are taken FNA concentration can be calculated. For the temperature and pH the first value that was measured on that day is taken, since those are the closest to the time when liquid samples are taken. Threshold values for AOB and NOB are discussed in Chapter 2.4.2.

- **Free ammonia (FA) concentration:**

$$NH_4{}^+ \rightleftharpoons H^+ + NH_3$$

<div align="right">Eq. 16</div>

$$FA = \frac{17 * NH_{4,eff}{}^+ - N * 10^{pH}}{14 * (e^{\frac{6344}{(273+T)}} + 10^{pH})}$$

<div align="right">Eq. 17</div>

Free ammonia also follows a dissociation equilibrium in aqueous solutions, as described in Eq. 16. For the calculation of the FA concentration also pH-value, temperature and the effluent NH4 concentration is determined. FA inhibition is also discussed in Chapter 2.4.2.

- **Hydraulic retention time (HRT):**

$$HRT = \frac{3000}{\dot{V}_{inf}}$$

<div align="right">Eq. 18</div>

HRT is the average time that the influent liquid stays in the reactor. It is calculated as the reactor's volume divided by the influent volumetric flow rate. The volume of the reactor amounts to 3000 mL. When hydraulic retention time equals solid retention time it also gives information about mean residence time of bacteria within the system. HRT equals solid retention time (sludge age) when sludge is withdrawn representatively and sludge is not accumulating in the system.

- **Oxygen uptake rate (OUR):**

$$OUR = \frac{DO_0 - DO_1}{t_1 - t_0}$$

<div align="right">Eq. 19</div>

OUR provides information about the bacterial activity of the sludge. OUR describes the amount of dissolved oxygen being consumed by aerobic bacteria in a certain time.

- **Nitrogen balance (N-balance):**

$$load_{NH4,eff} = \dot{V}_{inf} * NH_{4,eff}{}^+ - N \qquad \text{Eq. 20}$$

$$load_{NH4,conv} = \dot{V}_{inf} * NO_{x,eff} - N \qquad \text{Eq. 21}$$

$$N - balance = \left(\frac{NH_{4\,load,eff} + NH_{4\,load,conv}}{NH_{4\,load,inf}} \right) * 100 \qquad \text{Eq. 22}$$

- **N$_2$O Emission factor (EF):**

$$N_2O_{conc} = N_2O_{gas\,fraction} * \frac{273}{293} * 10^{-6} * \frac{44.01}{22.4} * 1000 \qquad \text{Eq. 23}$$

$$load_{N2O} = N_2O_{conc} * \dot{V}_{air} \qquad \text{Eq. 24}$$

$$load_{N2O-N} = \frac{2 * 14.0067}{2 * 14.0067 + 15.994} * N_2O_{load} \qquad \text{Eq. 25}$$

$$EF_{N2O-N/N\,load} = \frac{load_{N2O-N}}{load_{NH4,inf}} * 100 \qquad \text{Eq. 26}$$

$$EF_{N2O-N/N\,oxidized} = \frac{load_{N2O-N}}{load_{NH4,conv}} * 100 \qquad \text{Eq. 27}$$

Table 5: Symbols used for calculations with meaning and unit

symbol	meaning	unit
$load_{NH4,inf}$	influent NH_4^+-N loading rate	[mgN/d]
$\dot{V}_{inf}$	influent flow rate	[L/d]
$NH_{4,inf}^+ - N$	influent NH_4^+-N concentration	[mgN/L]
$NO_{x,eff}^+ - N$	effluent NO_x-N concentration	[mgN/L]
$NO_{2,eff}^- - N$	effluenNO_2^--N concentration	[mgN/L]
$NO_{3,eff}^- - N$	effluen NO_3^--N concentration	[mgN/L]
NAR	nitrite accumulation ratio	[ ]
-	ammonium removal degree	[%]
FNA	free nitrous acid concentration	[mgN/L]
FA	free ammonia concentration	[mgN/L]
HRT	hydraulic retention time	[days]
DO	dissolved oxygen concentration	[mg/L]
OUR	oxygen uptake rate	[mg/(L*h)]
$load_{NH4,eff}$	effluent NH_4^+-N load	[mgN/d]
$load_{NH4,conv}$	effluent NH_4^+-N load, converted	[mgN/d]
$N - balance$	nitrogen-balance	[%]
N_2O_{conc}	N_2O concentration	[mg/L]
$N_2O_{gas\,fraction}$	N_2O gas fraction	[ppm]
$load_{N2O}$	N_2O load	[mg/d]
$\dot{V}_{air}$	influent air flow rate	[L/d]
$load_{N2O-N}$	N_2O -N load	[mgN/d]
$EF_{N2O-N/N\,load}$	emission factor with regard to N-load	[%]
$EF_{N2O-N/N\,oxidized}$	emission factor with regard to N-conv.	[%]

4   Results and Discussion

The results of the lab-scale investigation will be presented in four figures for each of the four reactors. The first figure shows the overall process performance of the reactor. The secondary y-axis of the first figure shows the influent NH_4^+-N concentration and the effluent NH_4^+-N, NO_3^--N and NO_2^--N concentrations throughout the whole investigation period of the studies. On the primary y-axis of the first figure the NH_4^+-loading rate over the same period is depicted.

The second figure provides information about the HRT (primary y-axis) and the NAR (secondary y-axis) for each reactor. HRT is calculated as explained in Chapter 3.6. It is directly linked to the influent flow rate. Frequent clogging of the supply tubes lead to high HRTs. For this reason the primary y-axis of the second figure is cut down for each of the figures, in order to improve the illustration and to show a more relevant range of a lower HRT. Feed cloggings are indicated by the grey vertical connecting lines of the HRT graph. Since HRT can reach very high values, when clogging occurs, they are not explicitly illustrated in the figure.

The third figure shows the FA concentration, NH_4^+ removal degree (primary y-axis) and the pH-value (secondary y-axis) over time. The green transparent bar indicates the desired range of the ammonium removal degree of 50 – 60 %. A lower ammonium removal degree indicates process disturbances, e.g. an overloading. The orange transparent bar shows the critical range for pH-value of pH 7 - 7.5. pH > 7.5 can lead to FA inhibition, while pH < 7.0 can promote FNA inhibition. FNA concentration is not depicted in this figure. Based on the operation mode of high loading rate and high pH-value, FA inhibition plays a more significant role in SDE treatment. FNA inhibition occurs when nitrite accumulates and pH-value decreases below 7.0, e.g. when a clogging of the feeding tubes occur.

The fourth figure shows the accuracy of the nitrogen balance (primary y-axis) and the DO concentrations. The transparent grey bar shows the measurement uncertainty of 10 % for the analized parameters, which comes into account particularly for the calculation of the nitrogen balance. As almost no denitrifying processes are expected (high DO), N-balance should be close to 100 %. This way it can be ensured, that no nitrogen is denitrified to nitrogen gas (N_2), through heterotrophic bacteria or anammox. The contribution of

heterotrophic bacteria however is of minor importance as COD concentration in SDE is very low. Also anammox-activity is considered to be negligible due to high DO concentration. Values for N-balance decreasing down to 80 % can however be explained by spontaneously changing operation conditions, that need a certain time to be compensated in the N-balance, since N-balance is calculated on a daily basis, e.g. when the influent NH_4^+-N concentration significantly increases.

More detailed information upon the measurement values can be found in Table 17 for R1 and R2 and Table 18 for R3 and R4. Both tables can be found in the Appendix. The tables also include information regarding pH-value, temperature, dissolved oxygen concentration, NH_4^+ removal degree, and FA as well as FNA concentrations. The acronym "pd" in the tables stands for "process day". Values for pH-value, temperature and dissolved oxygen concentration represent the first recorded value of that day. When clogging occurs HRT reaches very high values indicated as "####", since an exact value in this case is not meaningful. . R1 and R2 were operated for 325 days, whereas R3 and R4 for 265 days.

Introduction:

Achieving a stable nitritation performance in CSTR is mostly a combination of many contributing factors. As already explained in Chapter 2 one important factor is the sludge retention time. It is based on a slower bacterial growth rates of NOB compared to AOB, which can cause a NOB wash-out, when low SRTs are chosen. This however, is based on the conditions of SDE of high ammonium concentrations and elevated temperatures. Another important factor are inhibition mechanisms of FA and FNA, influenced by pH-values, temperature and the ammonium and nitrite levels, respectively. In MBBR SRT is much higher than HRT, due to the formation of a biofilm. Other factors might become more important for this technology.

The initial fast increase of the nitrite accumulation ratio during start-up phase for all 4 reactors can most probably be attributed to the feeding mode that has been applied during this phase. During start-up no biofilm has formed upon the carrier media. For this reason MBBR can also be considered as a CSTR. For R1 and R2 phase A describes a discontinuous feeding mode up to process day 32, while for R3 and R4 phase A only lasts until process day 21. For the feeding procedure of phase A, high amount of substrate is added within a short time. This leads to a rapid increase of the pH-value causing, first of all NOB, but also AOB

inhibition. After the feeding procedure pH-value decreases slowly, since AOB are as well inhibited to a certain extent. Only when pH starts to decrease, due to recovering AOB activity, also NOB get the chance to recover and restart their metabolism. However, AOB, due to higher threshold values for inhibition, can recover faster and are therefore able to restart their metabolism earlier. By the time the pH-value reaches an appropriate level for NOB to operate and enough substrate (nitrite formed by AOB) is available for NOB, pH-value reaches a lower limit of around pH 6 – 6.2, where alkalinity limitations come into account and also the AOB conversion rate slows down until it ceases. At the same time low pH-values cause inhibition through FNA, which steadily increases day by day, since also nitrite accumulates. Based on these mechanisms, when a discontinuous feeding is applied, AOB will always have an advantage over NOB, regarding their susceptibility to these inhibitive compounds. However it has to be mentioned that this approach of feeding can only be applied for lab-scale experiments and is not applicable for full-scale SDE treatment.

When continuous feeding is applied, the system reaches a steady-state, where NOB activity is able to contribute to the conversion process and produce nitrate. Two main influencing factors that can possibly promote NOB activity are further studied in this thesis. Conversion of nitrite into nitrate is likely to occur, when first of all, NOB are less inhibited by FA nor by FNA. Or secondly, the solid retention time is high enough, allowing NOB growth rate to overcome the wash-out rate which is set by the hydraulic retention time. However, the second point does only affect suspended growth systems (CSTR) and cannot be consider as an influencing parameter for nitritation performance in MBBR, since sludge age is not controlled by HTR.

The first assumption for nitrate formation focuses on the FA and FNA inhibition through monitoring the pH-value. As mentioned in Chapter 2, high pH-values (7.5 - 8.5) are beneficial for FA inhibition and low pH-values (below 7.0) promote FNA inhibition, while the range between pH 7.0 – 7.5, might allow NOB recovery, as neither FA nor FNA intervenes or inhibits NOB metabolism.

The influences of these factors (temperature, pH-value, solid retention time, and FA and FNA inhibition) are studied in the course of this thesis in order to find out under which conditions NOB establishment can occur and which actions it requires to suppress NOB activity.

4.1 R1 - Reactor performance
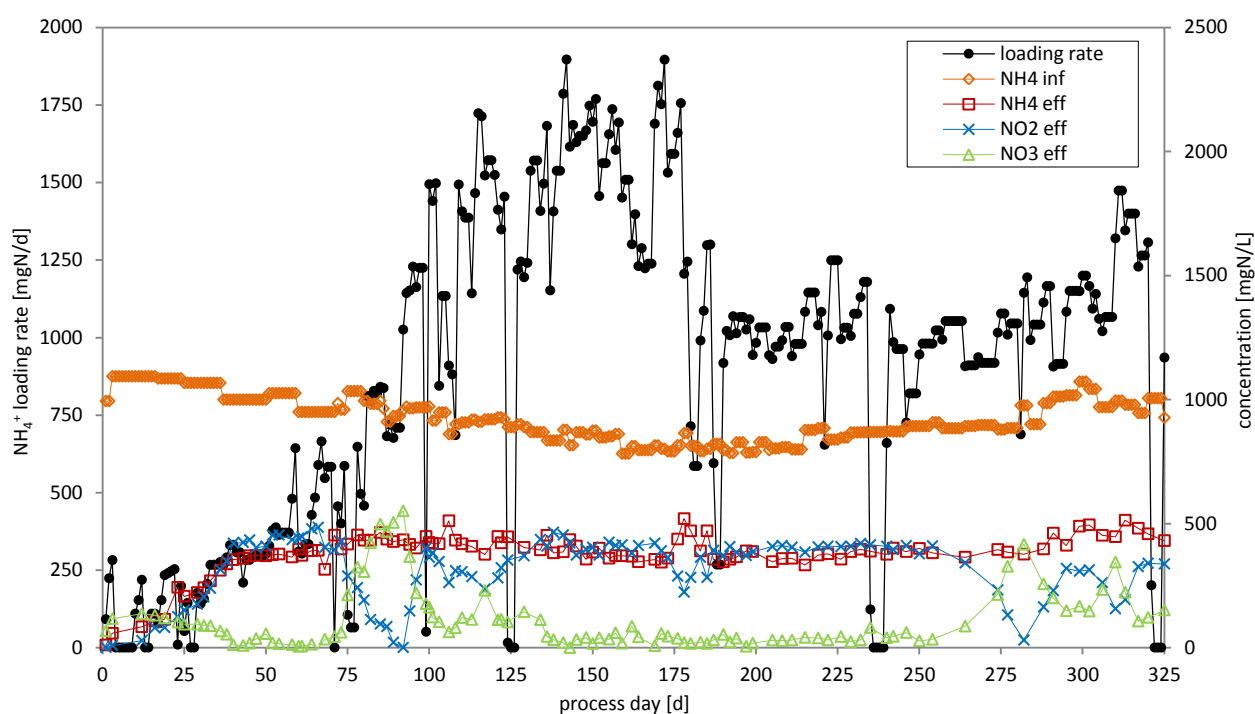
Figure 11: Reactor performance - R1
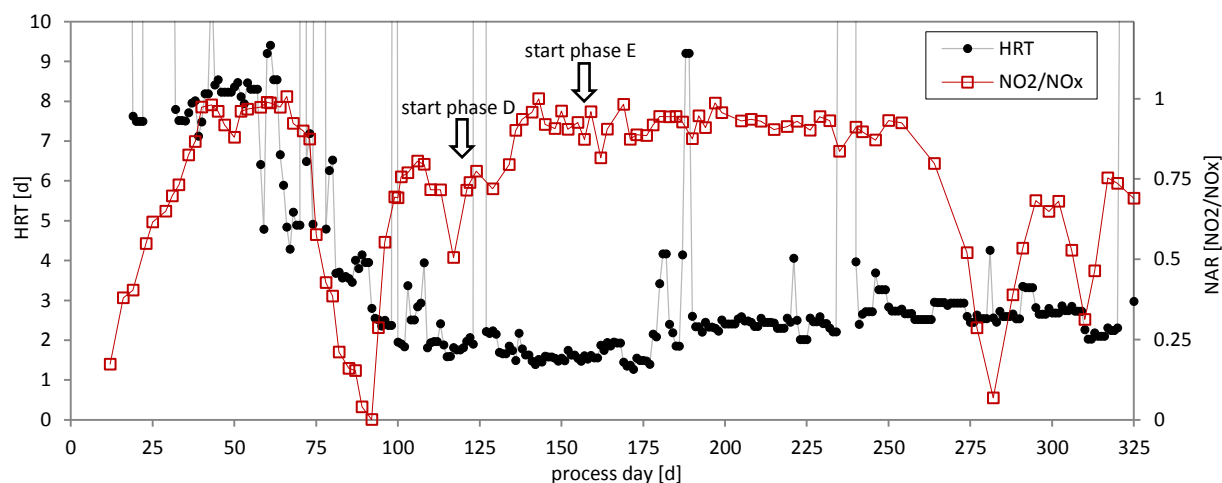
Figure 12: Nitrite accumulation ratio and hydraulic retention time over time - R1
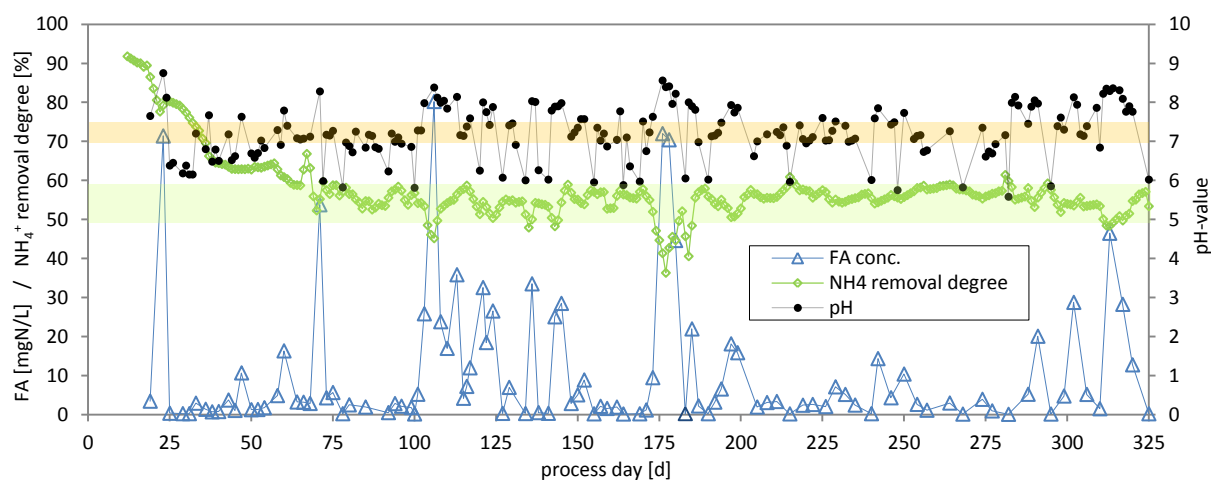
Figure 13: FA conc. / NH$_4$ removal degree / pH-value over time - R1
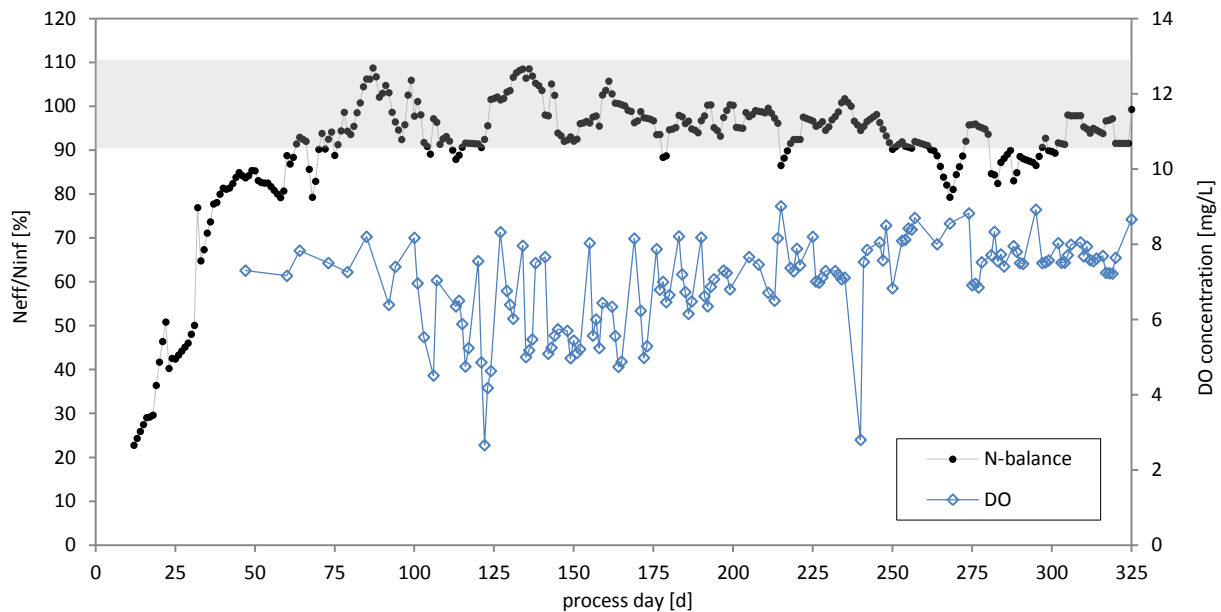
Figure 14: N-balance and DO concentration over time - R1

In Figure 11 the influent NH_4^+-N concentration can be seen. It is the same for all of the four reactors. It amounts to a mean value of 903 mgN/L NH_4^+ with a minimum value of 768 mgN/L in the summer period and a maximum value of 1094 mgN/L at the beginning of the investigation period. Decreasing influent NH_4^+-N concentration in the summer period can most likely be attributed to a problem of the centrifuge at the WWTP, where the feed was obtained.

Figure 11 also shows the effluent NH_4^+-N concentration over time. A steady increase can be seen up to process day 63, up to the point where it reaches a value of around 400 mgN/L. This period is characterized by the start-up phase, where microorganisms within the system still have to grow and accumulate. Also the NH_4^+-N content in the system still needs to accumulate, thus no meaningful conclusions regarding the NH_4^+ removal degree can be obtained. The removal degree between process days 35 – 63 steadily decreases from 70 – 60 %, until it remains steady between 50 – 60 % for the rest of the investigation time. A NH_4^+ removal degree of 50 – 60 %, shows stable reactor performance, with an effluent NH_4^+-N concentration ranging between 350 – 450 mgN/L. Exceptions are periods, where an overload of the system occurs. An overloading usually occurs, when whether NH_4^+ loading rates are set too high, the amount of sludge in the reactor decreases (due to enhanced sludge discharge), or temperature decreases. Overloadings are indicated by a high effluent NH_4^+-N

concentration and a decreasing NH_4^+ removal degree. The bacteria in the system are not able to convert all of the available substrate and NH_4^+-N accumulates. For this reason pH-value increases which leads to an AOB inhibition. A dosage of HCl is required in order to reduce the pH-value. Also the loading rate has to be adapted. For R1 an overloading occurred on process days 106 and between process days 176 − 185, as it can be seen in Figure 13. Low effluent NH_4^+-N concentration indicates a tube clogging. Since the bacteria do no longer obtain the required substrate. They consume all of the available substrate, up to the point, where a low pH-value causes inhibition through free nitrous acid. From process day 291 to the end of the investigation time, the effluent NH_4^+-N concentration steadily increases and reaches values between 450 − 500 mgN/L. The reason for this is the elevated NH_4^+-N concentration in the influent. The reactor during this time is operated at its limits (at high pH-value and NH_4^+ removal degree at around 50 %), in order to again achieve a high nitrite accumulation. More details upon this can be found later.

As mentioned in Chapter 3.2 for operation mode the NH_4^+-N Loading rate is adjusted, following the fluctuations of the pH-value. Since the amount of sludge, due to bacterial growth constantly increases, also the loading rate is increased over time. Loading rate can be increased up to the point where the amount of sludge reaches an equilibrium between bacterial growth and the amount of sludge which is withdrawn. Also in R1 loading rate is constantly increased following the pH-value. If pH-value reaches values above pH 8 loading rate has to be reduced. However, in Figure 11 it can be seen that sometimes loading rate falls down to 0, or is lower than the average. Reason for this can be a clogging of the supply tubes or a feed pausing due to overloadings. Figure 11 shows that the loading rate of R1 steadily increases up to 1900 mgN/d on process day 142. However this value is just a peak value, and the average maximum loading rate R1 amounts to about 1600 mgN/d. Also it has to be mentioned that during this time a high amount of sludge had accumulated, which leads to a higher NH_4^+ conversion performance of the reactor. When sludge age was better controlled in phase D and E loading rate amounts to an average of 1000 mgN/d.

Between process days 109 − 177 the loading rate fluctuates in a range between 1200 mgN/d and 1900 mgN/d. The average loading rate for this period amounts to 1500 mgN/d. Between process days 156 − 168 loading rate of R1 was constantly reduced from 1700 − 1200 mgN/d, although no overloading occured. The reason for this was an overloading in R3 and R4. All

reactors were connected to one feeding pump and the loading decreased in all reactors. Merely the size of the tubes for R1 was not changed in order to keep the loading rate at the same level. Between process days 169 – 177 this problem was solved and loading rate again amounted to about 1750 mgN/d. Between process days 177 – 190 loading rate experienced major fluctuations due to overloadings and the loading had to be reduced. Between process days 191 – 309 loading rate was successfully reduced to an overall average of around 1000 mgN/d, ranging between 900 mgN/d and 1200 mgN/d. The only exception represents a period between process days 235 – 240, where no feed was available, due to a feed supply bottleneck. In order to minimize bacterial death rate, the system was put into a stand-by mode by switching off the oxygen supply. Nitrifying aerobic microorganisms show slower death rates, when no oxygen is available. The reason for the reduction of the loading rate from a level of about 1500 mgN/d to 1000 mgN/d is difficult to explain. Maybe the enhanced control of the sludge age of phase E (process day 157) can only be seen by that time, or slightly decreasing temperatures towards autumn show their effects upon the bacterial activity. Also it has to be mentioned that during the period where loading rate of R1 amounted to an average of 1000 mgN/d there was also periods where pH-value was rather low ranging between pH 7- 7.50. Reason for nitrite accumulation during this time is a low HRT. The influence of FA inhibition was probably marginal. From process day 310 until the end of the investigation period the loading rate was slightly increased to an average of 1350 mgN/d.

As it can be seen in Figure 12 nitrite accumulation in R1 steadily increased up to process day 40 and remained stable up to process day 73 at a NAR of around 0.90. The feeding mode which is applied during phase A supports a high nitrite accumulation, as explained earlier. Phase A ended on process day 32 and went over to phase B. When the change from discontinuous feeding to continuous feeding took place, the loading rate tended to be too low, based on the measured pH-values most of the time ranging between 7 - 7.5 or even below 7. FA inhibition of NOB does not contribute to nitrite accumulation in this case. However nitrite accumulation remained high. A reason for this could be the feeding mode that has been applied in phase B. For the feed, diluted effluent of the reactor was used. This way nitrite of the effluent was recirculated and accumulated in the system. For the dilution, effluent was mixed with the influent SDE, which led to NOB inhibition in the influent feed tank, due to high pH-values. This way NOB activity was initially suppressed when recirculated

and bacteria were not able to perform full nitrification. Hydraulic retention time during this time amounted to approximately 8 days, while it has to be noticed that sludge was recirculated. Due to the recirculation SRT was higher than HRT. This way HRT is not informative regarding wash out rate of NOB.

Phase B went over to Phase C on process day 52, while nitritation remained stable up to process day 73. Between process days 64 - 68 pH-value was rather low and ranged between 7.05 – 7.12, which might allow a recovery of NOB activity, as explained earlier. FA concentration amounted to 2.85 – 3.22 mgN/L for a period of 5 days. Nevertheless, this did not show a significant effect upon nitrite accumulation. Anyways, hydraulic retention time during that time also decreased from an average of 8 days to approximately 4.5 days. This may have caused a NOB wash-out to a certain extent. Even though a continuous withdrawal through tubes in phase B tends to cause a sludge accumulation, not all bacteria responsible for the conversion processes are found in flocculent sludge. Also some of the bacteria can be found in very small flocks or in the bulk liquid itself and can thus be washed out also during continuous withdrawal.

On process day 71 R1 was slightly overloaded, indicated by a pH-value of 8.28 and increasing NH_4^+-N concentration in the effluent of 453 mgN/L. For this reason the feeding pump was turned off in R1 for one day. The following day the feed was switched on again. However NAR started to decrease by that day. One explanation for this could be, that the loading rate when the pump was switched on again, was not high enough and threshold values for FA inhibition were not reached. Rather low pH-values between 7.15 - 7.27 support this assumption. FA concentration on process day 73 and 75 was between 4 – 5 mgN/L. Also a lower loading rate between process days 75 – 78, which were caused by a clogging of the inlet pump, most probably contributed to an increased NOB activity. Up to process day 92 pH-value never reached levels higher than pH 7.25 and FA concentrations never reached values beyond 2.5 mgN/L. Along with low pH-values the nitrite accumulation decreased and reached 0 on process day 92. HRT during this time amounted to approximately 4.2 days. On process day 92 the loading rate was significantly raised from about 700 mgN/d to 1150 mgN/d. This led to a recovery of NAR on process day 94, 2 days later. pH-value on process day 93 amounted to 7.20, which does not indicate FA-inhibition per se. However it is possible due to the sudden increase of the loading rate, that pH reached values beyond 7.5

during the night. Nevertheless, because of high conversion capacity of AOB, pH again decreased to a more moderate range by the time pH-values was measured. This might have caused NOB inhibition for at least a few hours. However, the main factor for a higher nitrite accumulation is a decreasing HRT from 4 days to 2.5 days, which could have caused an NOB wash-out.

Loading rate increased even further up to 1500 mgN/d by process day 102. For this reason also nitrite accumulation ratio increased up to a level of 0.77. HRT, at the same time, decreased to an average of 2 days. The small decrease of NAR from 0.81 to 0.72 between process days 106 – 110 is difficult to explain. Regarding the high pH-values during this time ranging from 7.84 - 8.38 FA inhibition of NOB must have caused an increase of NAR, rather than a decrease. FA concentration ranged between 20 – 80 mgN/L. Perhaps the small reduction of the loading rate, due to high pH-values on process day 106, led to a lower wash-out rate of NOB. HRT amounted to 3 - 4 days during that time. Nevertheless, pH-values below 7.5 the following days, between process days 113 – 117, probably led to a decrease of NAR from 0.71 – 0.51 despite of an increase of the loading rate. On the other hand on process day 121 NAR again amounted to 0.72. The lower nitrite level on process day 117 (NAR at 0.51) can eventually also be attributed to measurement errors, since decreasing NAR between process days 113 - 121 can hardly be explained. However during that time, shortly before phase D started, it has to be noticed that a high amount of suspended solid was noticed in R1. This might lead to the conclusion that over a long time of continuous withdrawal by pumping through thin tubes a high amount of sludge had accumulated within the reactor. It would imply that the HRT is far from SRT and therefore is very little representative for explaining a bacterial wash-out. This would allow NOB to stay in the system despite of low hydraulic retention times.

At the beginning of phase D on process day 121, NAR remained more or less stable at a level of 0.72 – 0.79 between process days 121 – 134 with a loading rate ranging from 1200 – 1500 mgN/d and a HRT between 1.7 - 2.2 days. Also pH-value amounted to an average of 7.50, except for a clogging on process days 125. On process day 136 and 137 pH-values increased to 8.03 and 8.01, although no significant increase of the loading rate was applied. A logical conclusion could be that the more efficient sludge discharge in phase D started to show its effect. With less sludge in the system also the performance decreases and pH rises.

However, with a higher pH-value the NOB inhibition showed the desired effect and NAR increased from 0.79 – 0.90 on process day 134. FA level reached 33 mgN/L during that time. Since there was no indication for an overload, the loading rate was kept constant at this level. As soon as NAR again increased, R1 experienced a long period of stable nitritation. Between process days 136 – 254 NAR amounted to an average of 0.92 for a period of 120 days. On process day 157 phase D also went over to phase E, where biofilm was removed from the reactor walls on a daily basis. Discontinuous sludge withdrawal in phase D and E appears to show the desired effect, since solid retention time is more effectively controlled and an efficient NOB wash-out is achieved.

For 32 days, between process days 136 - 168, NAR amounted to an average of 0.92 an average of 1500 mgN/d for the loading with isolated cloggings or peaks and an average of 1.65 days for HRT. Even longer periods with moderate pH-values, that could promote nitrate production did not show any NOB activity. Also this can be attributed to the feeding mode applied in phase D and phase E, allowing an enhanced control of the sludge age. For instance, between process days 148 – 150 or 156 – 162, with pH-values ranging from 7.12 – 7.35 or 6.87 – 7.35, respectively, nitrite accumulation did not decrease.

Between process days 169 – 191 R1 experienced high fluctuations of the feed. Between process days 176 - 190, the loading rate had to be adjusted, due to overload of the system, indicated by pH-values ranging from 8 – 8.5 for about 5 days. A dosage of 2 mol/L hydrochloric acid (HCl) was performed 3 days running, but did initially not achieve the desired effect on the reactor performance. Finding the appropriate loading rate during this time ended in high fluctuations of the NH_4^+ loading rate. A reduction of the loading rate was the consequences in order to allow the system to recover. High pH-values during the period of overloading promoted NOB inhibition. Nitrite accumulation ratio remained high. A clogging between process days 180 – 183 may have caused FNA inhibition due to low pH-values. Since the loading rate after the clogging was high enough and pH on the following day amounted to a level of 8.00, also here nitritation performance remained stable. However after the clogging between process days 187 – 190, pH amounted to 7.13 on process day 191 and did not reach inhibitive levels for FA inhibition. Since the solid retention time amounted to approximately 2.3 days this could be the reason, why NAR did not decrease, even though FA inhibition was low.

Between process days 191 – 254 a long time of stable operation was achieved, except for process days 235 – 240, where no feed was available, due to a bottleneck of feed supply. Nitritation maintained stable up to process day 254. Loading rate amounted to an average of 1000 mgN/d, excluding the phase of the feed supply bottleneck. HRT amounts to about 2.6 days. Also here the more efficient control of the sludge age showed its effect, since also periods with low NOB inhibition through FA (pH-values between 7 – 7.5), did not lead to a recovery of NOB activity. It seems like once HRT is low enough at given temperatures, NOB wash-out is achieved and no more FA inhibition is required.

However, between process days 253 – 257 pH-values ranging from 6.73 – 7.16, with a HRT of about 2.7 days probably caused the decrease of NAR from 0.92 – 0.73. On process day 246 the temperature of R1 fell below 21 °C for the first time since the beginning of the investigation period. Maybe this could have also caused a small advantage for NOB over AOB and the wash-out rate of NOB was no longer high enough. The differences of the specific growth rates between AOB and NOB become smaller with decreasing temperature. This could mean that the HRT of 2.7 days was no longer sufficient in order to achieve NOB wash-out. Between process days 254 – 257 the temperature ranged between 20.4 – 20.7 °C.

Between process days 254 – 282 nitrite accumulation ratio further decreased from 0.91 – 0.07. It has to be noticed that between process days 257 – 274 discontinuous withdrawal procedure was replaced by continuous withdrawal through tubes like in phase C. The reason for this was a long time of holidays. Through continuous withdrawal, SRT became higher than HRT, since sludge in the system slowly accumulated. HRT during this period ranged between 2.5 – 3 days, while SRT was significantly higher. For this reason an effective NOB wash-out was not achieved and might be the reason for a decreasing nitrite accumulation. Discontinuous withdrawal again started on process day 274. Even though HRT until process day 282 amounted to an average of 2.5 days, NAR still decreased and NOB wash-out was not achieved. However pH-values during that time stayed below 7.00 for most of the time. Hence FA inhibition of NOB occurred. The reason for low pH-values could be the high amount of sludge in the system, which accumulated during winter holidays, allowing the system to achieve a higher ammonia conversion. Only by process day 283 pH-value suddenly increased to 7.99, although loading rate was not significantly increased. Maybe the change from continuous to discontinuous withdrawal method started to show its effect and the

amount of sludge in the system decreased. However, the sudden increase of the pH-value caused NOB inhibition and nitrite again accumulated in the system, even though HRT remained constant. On process day 288 NAR again reached 0.39 and kept on increasing until process day 302. pH-value fell down to 7.18 and 7.14 on process days 304 and 305 and caused a decline of NAR down to 0.31 by process day 310. Loading rate was then significantly increased on process day 310 from approximately 1000 mgN/d to almost 1500 mgN/d, with a HRT decreasing from 2.7 days to 2.0 days. Increasing loading rate and the pH-value brought the desired effect and NAR again climbed up to 0.75 on process day 317 and remained at this level until the rest of the investigation time.

4.2 R2 – Reactor performance
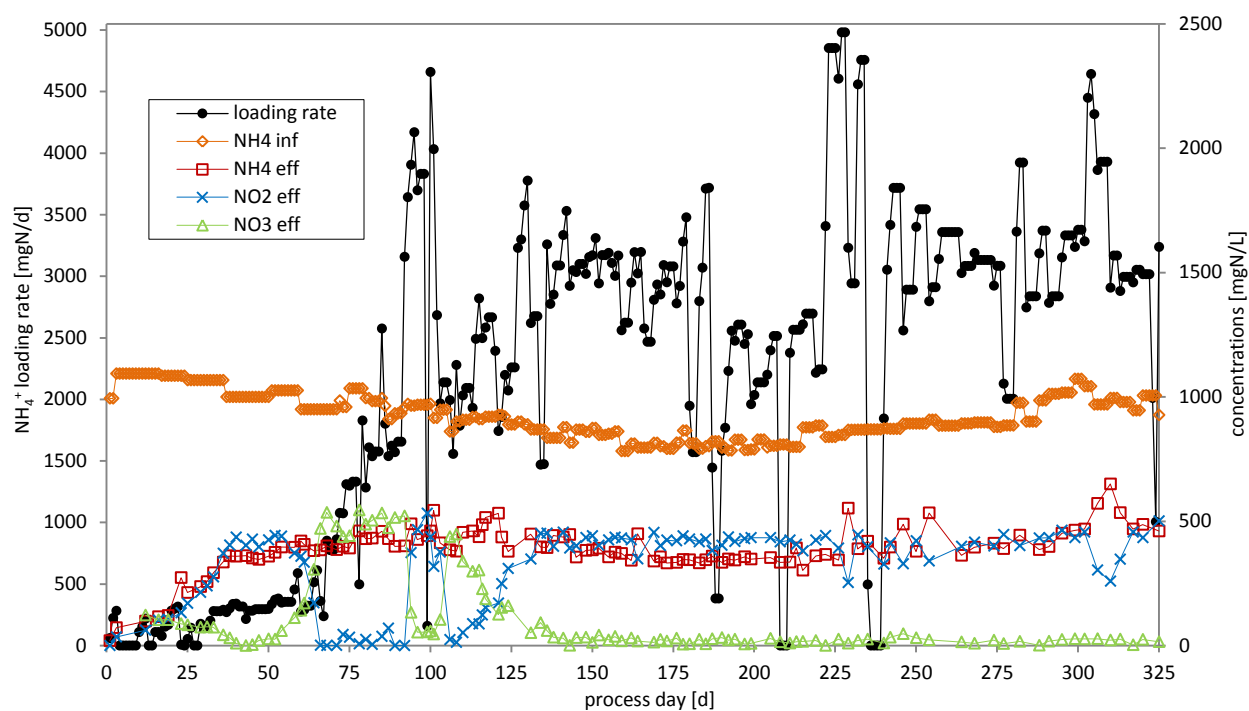
Figure 15: Reactor performance - R2
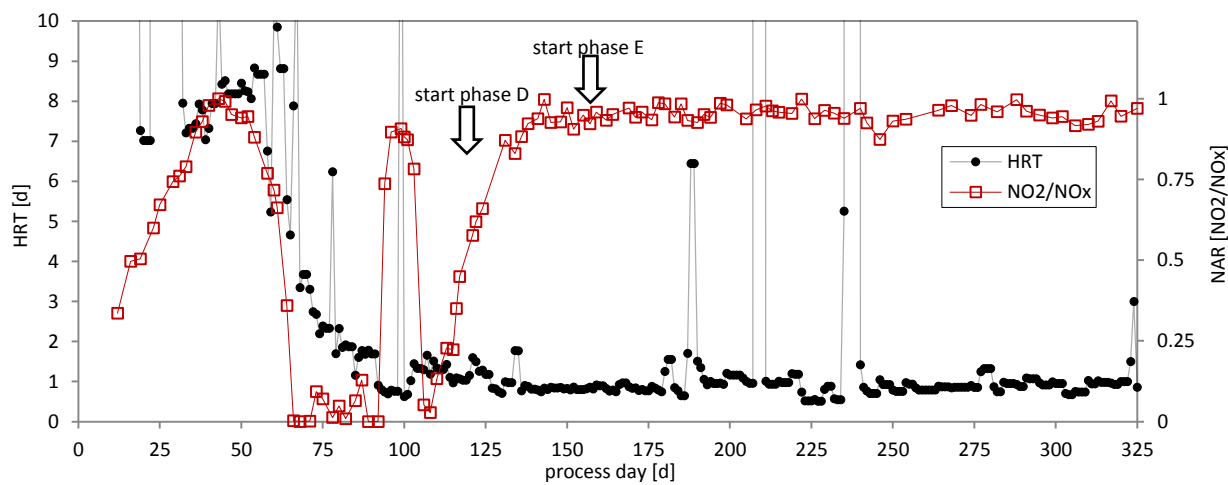
Figure 16: Nitrite accumulation ratio and hydraulic retention time over time - R2
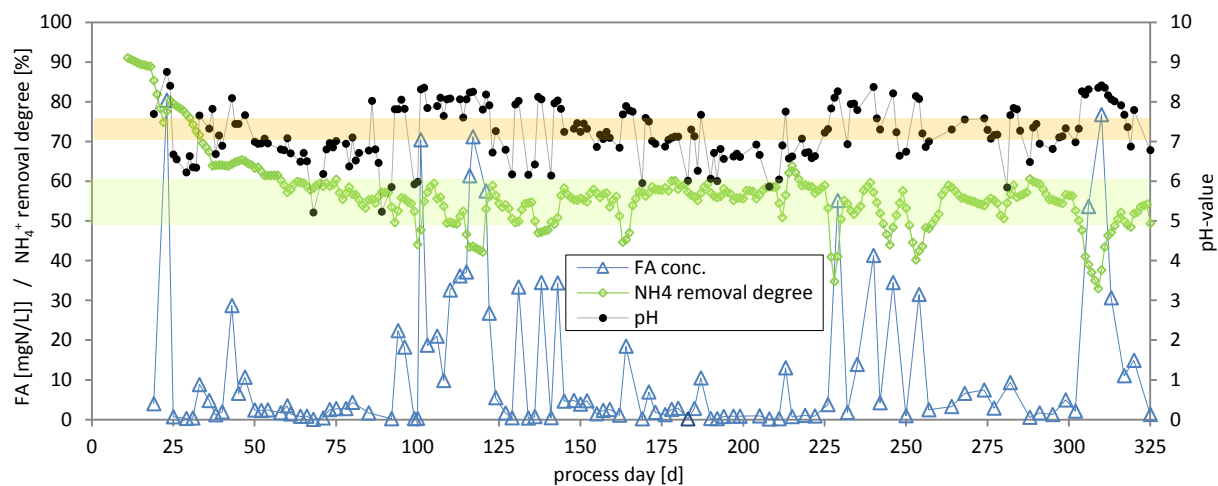
Figure 17: FA conc. / NH4 removal degree / pH-value over time - R2
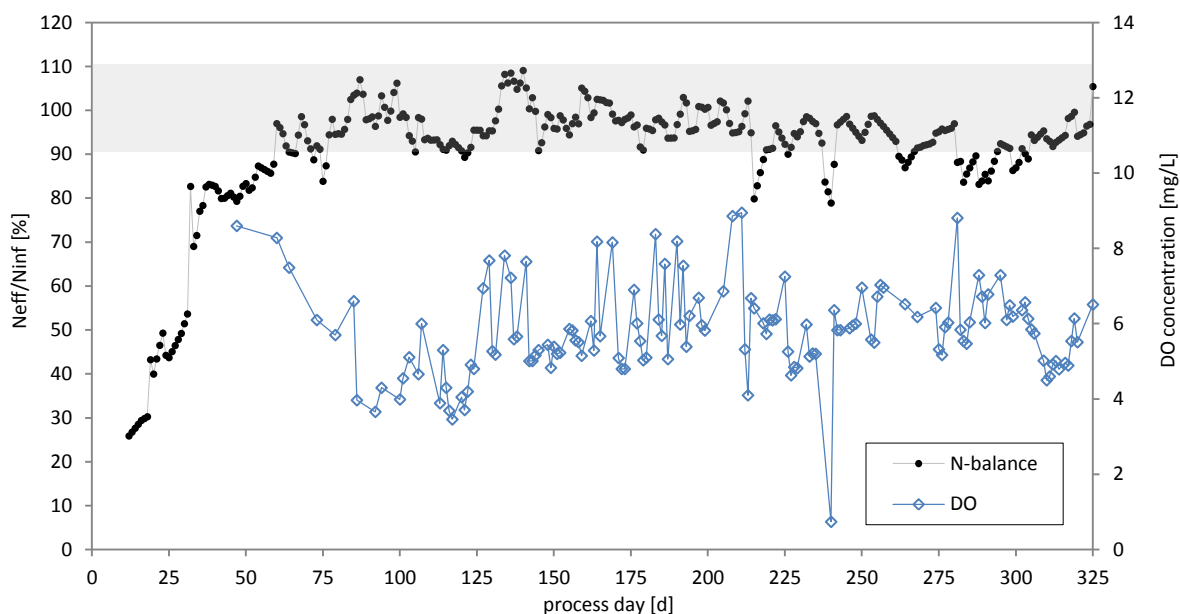
Figure 18: N-balance and DO concentration over time - R2

The effluent NH_4^+-N concentration in R2 shows similar development as in R1 for the start-up phase, as shown in Figure 15. Also in R2 the ammonia within the system needs to accumulate until it reaches a certain point, where bacterial conversion rate and NH_4^+ loading rate both reach an equilibrium based on the alkalinity limitations in SDE. Up to process day 60 NH_4^+-N concentration in the effluent remains below 400 mgN/L. Like in R1, once the start-up phase has ended the effluent NH_4^+-N concentration in R2 ranges between 350 – 450 mgN/L when no overloadings occur. NH_4^+ removal degree of 50 – 60 % under stable reactor performance is the same. As it can be seen in Figure 17 overloadings occur on process day 94 and 101, between process days 116 – 121 on process day 229, 246 and 254 and between process days 306 – 313.

Up to process day 91 loading rate was steadily increased up to 1650 mgN/d (except for process day 85 with an NH_4^+ loading rate of 2500 mgN/d). Due to a low nitrite accumulation up to process day 92 loading rate was significantly increased on that day. More details upon nitritation performance can be found later. Between process days 92 – 101 loading rate amounts to an average of 4000 mgN/d. On process days 101 an overload occurs and the loading rate again had to be reduced drastically. The effluent NH_4^+-N concentration was able to stabilize by process day 103. Between process days 103 - 126 the loading rate remained more or less stable and amounted to an average of 2000 mgN/d. Due to low pH-values it

was possible to again increase the loading rate. After a rapid increase of the loading rate between process days 127 - 130, followed by some minor cloggings on process days 134 - 135, on process day 136 an appropriate loading rate was found. Between process days 136 – 179 the loading rate amounts to an average of 3000 mgN/d. Between process days 179 – 194 R2 was exposed to high feeding fluctuations, due to frequent supply tubes clogging. Between process days 192 – 221 the ammonium loading remained rather stable at an average value of 2500 mgN/d. Only between process days 226 – 264 frequent fluctuations in the effluent NH_4^+-N concentration for more than 40 days is noticeable. The reason for this is most probably a steep increase of the loading rate on process day 221 – 223 up to 4850 mgN/d, which caused an overloading of the system. Between process days 223 - 234 the average loading rate amounts to approximately 4350 mgN/d, followed by a bottleneck of the feed supply of 5 days on process days 235 - 240, as discussed earlier. After these 5 days of system shut-down R2 was no longer able to handle the same loading rate that has been applied before. Between process days 241 – 302 loading rate amounts to about 3100 mgN/d. A small clogging between process days 277 – 280 and the following high loading of around 3900 mgN/d did not show any noticeable effect on the NH_4^+ removal degree or nitrite accumulation, which indicates a stable reactor performance. An increase of the loading rate from process day 302 – 308 from 3300 mgN/d to 4650 mgN/d caused a clear overload of the system. The loading rate again was adjusted to the initial loading rate of about 3000 mgN/d by process day 310. The loading rate remained at this level until the end of the investigation period.

Figure 15 shows that nitrite constantly accumulated up to process day 43 in R1. Nitritation was therefore successfully promoted during this time. In the start-up phase carrier media in R2 can also be seen as inert, since biofilm needs a certain time to attach and grow on the carrier media. Up to process day 32 (end of phase A) also discontinuous feeding procedure like in R1 was applied. This obviously also proved to be an effective method for R2 in order to promote nitritation. Starting with phase B, between process days 32 – 47, the switch to continuous loading in R2 also showed positive results. Loading rate amounted to an average of 300 mgN/d, HRT ranged between 7 – 8 days and pH-value was very often close to 7.5 or higher. The concentration of free ammonia probably exceeded the threshold values and promoted NOB inhibition. Between process days 50 – 66 pH-values started to decrease and pH ranged between 6.50 – 7.08, while loading rate remained more or less stable. NOB

inhibition diminished and NAR dropped from 0.94 to 0 within 16 days. It was observed, that bacteria started to attach on the carrier media during this period and started to form a biofilm. On process day 59 carrier media were studied under a M3Z ZOOM stereomicroscope from Wild Heerbrugg and an initial biofilm structure was detected. A picture can be seen in Figure 20. Chances are high that among these colonies also NOB were able to establish, which inter alia caused a decreasing NAR in R2. Between process days 66 – 92 NAR remained below 0.13 for 26 days, although loading rate was significantly increased and ranged between 1500 – 1800 mgN/d for most of the time. Also pH-value remained below 7.10. The only exception is process day 85, where loading rate was increased to 2600 mgN/d but then immediately decreased the following day. This led to an increase of the pH-value up to 8.02 the following day and a very small increase of NAR with a value of 0.13 two days later. Merely FA level which caused NOB inhibition was not determined on process day 86. However, NAR again dropped, since loading rate was again reduced.

On process day 92 the loading rate was successfully increased from 1600 to 3150 mgN/d, without causing an overload the following day. pH-values climbed up to values above 7.80 and stayed at this level. Within 4 days NAR again reached a value of 0.90 on process day 96. By process day 100 loading rate reached 4650 mgN/d, which caused an overload the following day. Loading rate was again drastically reduced to about 2000 mgN/d by process day 103. Between process days 103 – 106 NAR again dropped very fast down to 0.05 and remained low for the following days.

A very interesting finding can be seen between process days 100 – 121 when phase D started. After the significant reduction of the loading rate from 4000 – 2000 mgN/d pH value remained very high up to process day 121. pH-value ranges between 7.84 – 8.25, except for process day 114 with a pH-value of 7.60. Also the loading rate was increased up to 2800 mgN/d by process day 115 and then again reduced to 2400 mgN/d by process day 120. Consequently HRT is very low ranging between 1 – 1.5 days. NAR however increased only slowly. Between process days 106 – 121 it was only able to increase from almost 0 to 0.58 by process day 121. This leads to the conclusion that a major part of NOB must be found in the biofilm, attached on the carrier media. By stressing NOB through very high loading and creating unfavourable conditions it was possible to displace NOB by AOB on the carrier media.

Due to decreasing pH after process day 122 also loading was increased up to an average of 3000 mgN/d and stayed more or less at this level until process day 177. By process day 138 NAR again reached a level above 0.90 and remained at this level for the rest of the investigation time. After this period of frequent up and downs of the NAR of this MBBR system, it seems like the establishment of an ideal biofilm for maintaining a high nitrite accumulation has been achieved. Even long periods with low or moderate pH-values did not negatively affect nitrite accumulation of R2. This can be seen for example between process days 155 – 162, where pH ranged between 6.86 – 7.24, or between process days 176 – 180, with pH-values between 6.87 – 7.12. Another period with very low pH-values can be found during process days 218 – 222, with pH between 6.58 – 7.07. During any of these periods NAR showed any signs of a decline. Suspended growth systems periods under these conditions frequently show a recovery of the NOB activity, as it can be seen in the discussion for R1.

And even though HRT for R2 is very low, a low sludge age cannot be the reason for the stable nitrite accumulation. It is undeniable that sludge is also washed out in MBBR systems. The thickness of the biofilm is determined by the equilibrium between the bacterial growth-rate of the biofilm and the mechanical shear forces among the carriers themselves, which cause a biofilm abrasion. For this reason biofilm in MBBR does only reach a certain thickness which is limited by these effects (Piculell, 2016). However it can be said that nitritation in such a system cannot effectively be controlled and regulated by setting a HRT. SRT and HRT in MBBR are completely different and sludge age can almost be seen as indefinite.

4.2.1 Biofilm build-up of R2

| 07.06.17 (process day 59) | 01.08.17 (process day 114) | 09.08.17 (process day 122) | 23.02.18 (process day 320) |
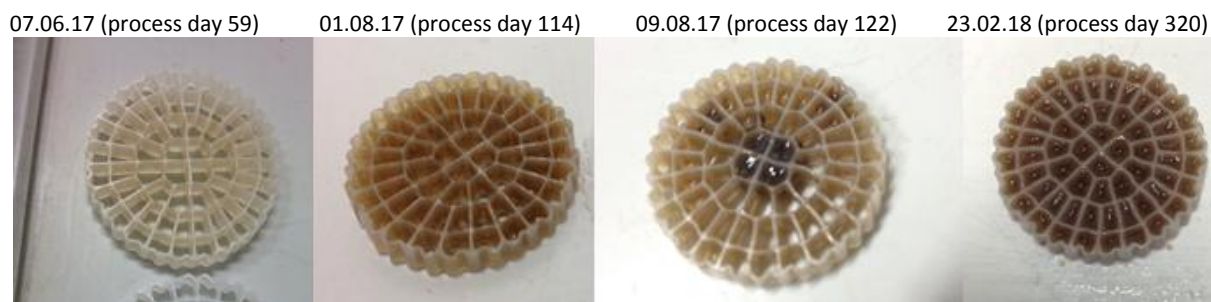
Figure 19: Development of the biofilm upon the carrier media over time
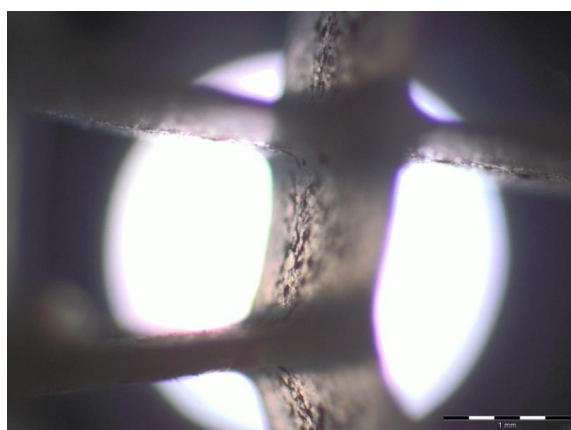
Figure 20: Biofilm build-up on carrier media on process day 59 – picture taken by M3Z ZOOM stereomicroscope from Wild Heerbrugg

In Figure 19 the development of the biofilm over time can be seen. The first picture shows the moment, when biofilm build-up was firstly noticed on the carrier media. The same day the carriers were studied under a M3Z ZOOM stereomicroscope from Wild Heerbrugg. Figure 20 shows a picture of this biofilm under the microscope. With the naked eye, only a slight brown tone can be seen. Under the microscope it can be observed that especially in the well-sheltered voids an initial biofilm structure started to attach onto the carrier media. Due to the low nitrite accumulation of R2 during that time, those colonies were assumed to consist of both AOB and NOB. Low HRT during this time did not achieve NOB wash-out. The second picture in Figure 19 shows a well-established biofilm on the carriers by process day 114. Picture number 3 shows that a notable amount of sludge is able to accumulate within some of the cavities, while others are less covered with sludge. Picture number 4 on the other hand shows the carrier media in a very advanced state. All of the available voids and cavities are fully covered with sludge. A large amount of sludge is present in R2 during this period.

4.3 R3 – Reactor performance
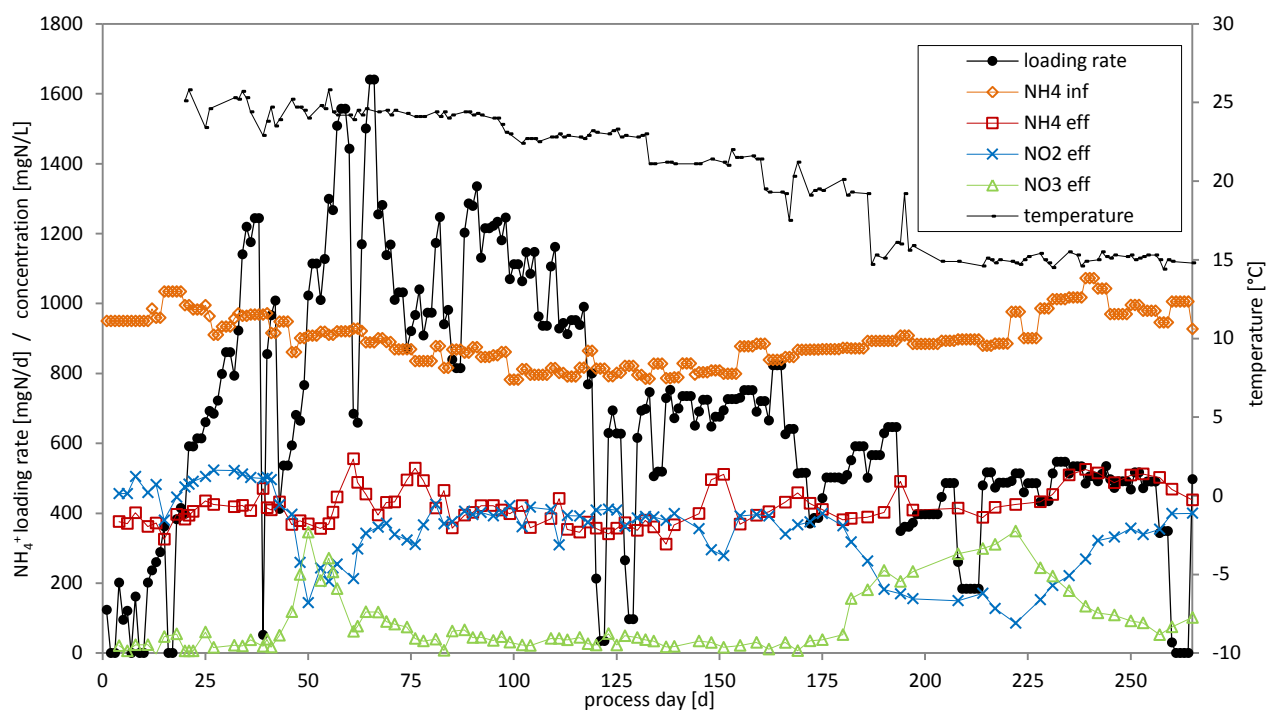
Figure 21: Reactor performance - R3
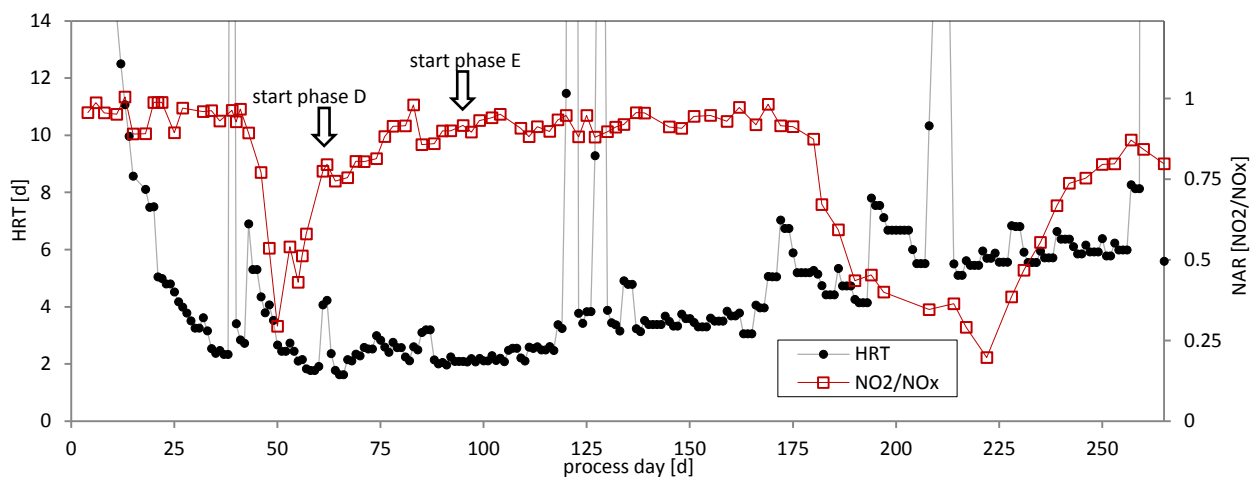
Figure 22: Nitrite accumulation ratio and hydraulic retention time over time - R3
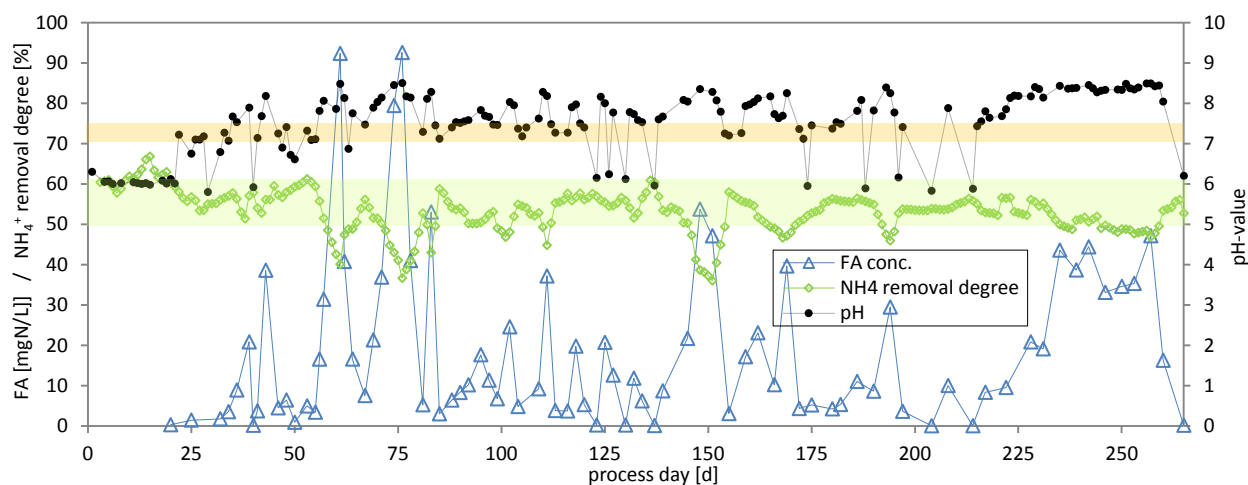
Figure 23: FA conc. / NH4 removal degree / pH-value over time - R3
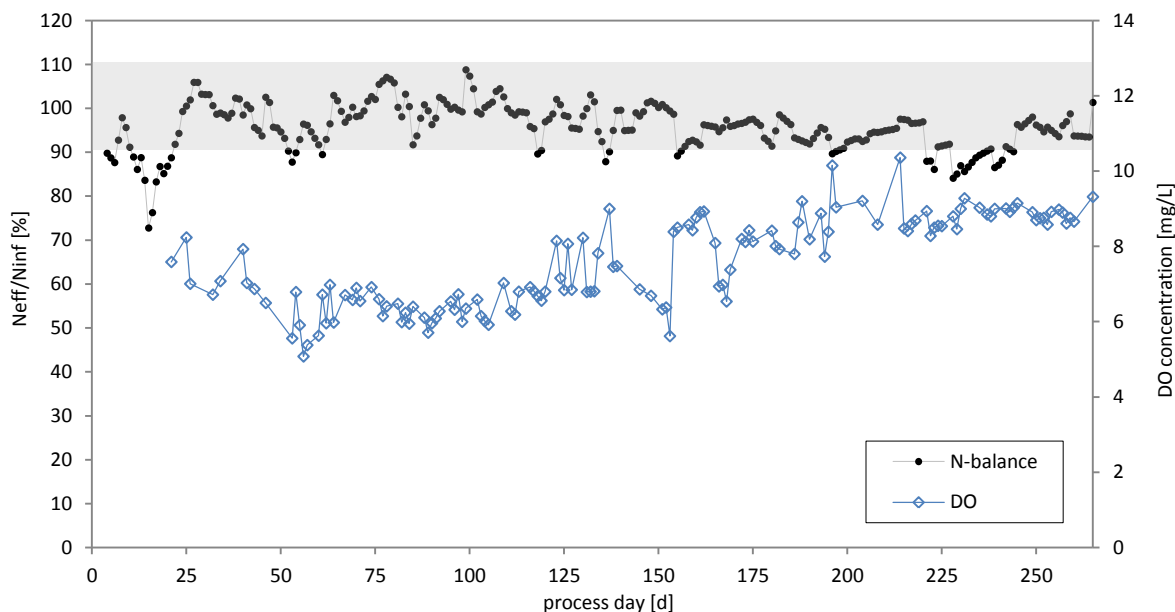
Figure 24: N-balance and DO concentration over time - R3

R3 applies a continuously stirred tank reactor (CSTR) like R1. For this reason similar results are expected. However the influence of decreasing temperature over time on the nitrite accumulation of R3 is to be studied. For an ambient temperature range between 22 – 25 °C, a similar performance to R1 is awaited, while for a lower temperature range between 20° - 15 °C, the system might show different values for the influencing parameters or it will show a total different behaviour.

In Figure 21 the reactor performance of R3 is illustrated. Like in R1 and R2 the influent ammonium concentration is equal to the one of the other reactors. Unlike in R1 and R2 the effluent NH_4^+-N concentration was at a very high level from the beginning on, since R3 and R4 used the effluent of R1 as seed sludge for inoculation. Like in R1 and R2 a stable operating mode for R3 can be found for an effluent NH_4^+-N concentration ranging between 350 – 450 mgN/L in order to achieve a NH_4^+ removal degree of 50 – 60 %.

As it can be seen in Figure 23, overloadings for R3 occur on process day 61, between process days 74 –78, on process day 83 and 111, between process days 148 – 151 and on process day 194.

From process day 230 until the end of the investigation time the effluent NH_4^+-N concentration started to increase up to values between 450 – 520 mgN/L, without indicating

a major overloading. However during this time R3 was operated at its limits, since NH_4^+ removal degree was very close to 50 % and occasionally even falls below 50 %. Also pH-value during this time constantly stayed above pH 8.

Table 6: Temperature profile of R3

process day	temperature	NH_4^+-loading rate	comment
56 – 96	24.5 °C ± 0.6 °C	-	-
97 – 132	22.9 °C ± 0.7 °C	950 – 1100 mgN/d	-
133 – 160	21.3 °C ± 0.7 °C	approx. 750 mgN/d	-
161 – 186	19.3 °C ± 0.8 °C	500 – 600 mgN/d	except for process day 167 (17.5 °C), process day 168 (20.3 °C), process day 169 (21.2 °C)
187 – 265	15.1 °C ± 1.0 °C	400 – 450 mgN/d	except for process day 195 (19.2 °C)

Table 6 shows the temperature profile with the corresponding ammonium loading rate of R3 throughout the investigation period. Temperature of R3 remained uncontrolled up to process day 46, when the thermostat of the water bath was installed and set to 25 °C. After some days of finding the proper method for the thermostat and the water bath, temperature was successfully controlled and monitored.

Loading rate was constantly increased during start-up until it reached 1250 mgN/d on process day 38. On process day 21, phase A went over to phase C with continuous loading and undiluted feed. Phase B was skipped since no feeding with diluted feed was applied. Between process days 38 – 43 the loading rate experienced some fluctuations and cloggings. A high pH-value of 8.18 on process day 43 was wrongly interpreted as an overloading, since NH_4^+ removal degree was still above 53 % on that day. However the loading rate was significantly reduced to about 400 - 500 mgN/d. Between process days 43 – 59 loading rate was again steadily increased until it reached 1550 mgN/d. Due to overloading, loading rate was again decreased in order to let the system recover. Loading rate went back to a level of 1600 mgN/d that has been applied before. Between process days 66 – 87 loading rate was again steadily reduced since another overloading occurred. On process day 88 loading rate was significantly increased to about 1200 – 1300 mgN/d. However, due to the reduction of

the temperature on process day 97 loading rate was also slowly decreased between process days 98 – 117 from approximately 1250 to 950 mgN/d. Between process days 118 – 130 loading rate experienced two cloggings. By process day 131 loading rate again stabilized and remained stable until process day 161 and ranged between 700 – 750 mgN/d for most of the time. On process day 161 temperature was again decreased to 19 °C and loading rate was steadily reduced until it ranged between 500 – 600 mgN/d up to process day 189. On process day 186 temperature was further reduced down to 15 °C and the loading rate after 4 days had to be reduced from 650 mgN/d to 350 mgN/d on process day 194, due to overloading. From process day 197 until the end of the investigations loading rate remained at a level between 400 – 550 mgN/d, except for cloggings on process days 208 – 214 and process days 257 – 264.

As it can be seen in Figure 22 NAR of R3 remains stable up to process day 43. Phase A went over to phase C on process day 21, which initially had no effect on the nitritation performance. Loading rate constantly increases up to 1250 mgN/d and a high nitrite accumulation was this way supported. However in phase C, sludge in the system began to accumulate, due to the way of sludge withdrawal. A clogging on process day 39 did not show a major effect upon nitrite accumulation. However the high pH-value on process day 43 was misinterpreted as an overloading, which led to the decision of reducing the loading rate for the weekend. This measure led to a decline in NAR from 0.89 – 0.77 since pH-value became too low and NOB inhibition through FA became lower. Also HRT became higher and wash-out rate of NOB consequently became lower. Moreover, after a long time of continuous withdrawal through thin tubes the amount of sludge in the system became significantly higher. Between process days 46 – 50 pH-values never exceeded pH 7.41. This leads to the conclusion, that due to the high amount of sludge in the system the reactor would have been able to handle a higher loading rate. By process day 50 NAR dropped down to 0.29. Low pH-values lead to the decision of significantly increasing the loading rate between process days 48 - 51 from 600 to 1100 mgN/d. NAR again increased and ranged between 0.43 – 0.58 between process days 53 – 58. When pH-value reached values above pH 7.50 between process days 56 – 74 and the loading rate was further increased to 1000 – 1600 mgN/d, NAR was able to recover up to a level of about 0.80. Also phase C went over to phase D (discontinuous sludge withdrawal) on process day 61, which probably was also supportive for nitrite accumulation. Due to steadily decreasing sludge amount within the

system in phase D, loading rate also had to be reduced again. Between process days 74 – 87 loading rate again decreased and stabilized in a range between 800 – 1000 mgN/d. NAR during that time ranged between 0.86 – 0.98. Between process days 85 - 180 R3 experienced a long time of a very stable nitration performance. On process day 97 phase D also went over to phase E. Discontinuous sludge withdrawal also here proved to be an effective method in order to achieve a high nitrite accumulation. Up to process day 180 temperature was decreased to about 19.5 °C. As a response to decreasing temperature also loading rate had to be adapted and dropped down to about 500 – 600 mgN/d. Between process days 148 – 151 an overloading occurred, which however did not show an effect upon nitrite accumulation. The system moreover was able to recover fast and without further changes on the operation mode.

When NAR again started to decrease down to 0.67 on process day 182, pH-value was constantly below 7.53 for about 10 days. For this reason FA inhibition probably lost its impact. Also between process days 172 – 175 R3 experienced a clogging. Loading rate decreased from 600 mgN/d to about 300 – 400 mgN/d for 5 days and HRT increased to 6 – 7 days. Maybe the combination of both important parameters caused a decline of nitrite accumulation. The reason for an increasing NOB activity the following days is very hard to explain. Loading rate and HRT between process days 182 – 194 were both at a very similar level to the values, before NAR decreased. Also pH-value was most of the time above 7.80. However on process day 187, temperature was significantly decreased from 19 °C to about 15 °C, when NAR already fell below 0.60. It seems like the system requires a longer time to regain nitrite accumulation under these unusual conditions of relatively low temperatures, once a certain level of NAR is lost. Further decrease of NAR between process days 194 – 222, down to 0.20. This can be attributed to the winter holidays and the change from discontinuous to, again, continuous sludge withdrawal through thin tubes. This way sludge accumulation is supported and efficient NOB wash-out is not achieved. Winter holidays ended on process day 214 and withdrawal mode was changed from continuous to discontinuous withdrawal. However, only by process day 222 this started to show the desired effect. Sludge in the system became less and the pH-value again increased to values above pH 8. pH-values remained at this level until the end of the investigation period. Loading rate at the same time was not further increased and amounted to a constant average of 500 mgN/d. However nitrite accumulation only slowly recovered and NAR

reached its maximum on process day 250, 28 days later, with a NAR of 0.80 and remained at this level also after the review period. The reason for the slow recovery might lie in the NOB growth rate at lower temperatures. The difference between AOB and NOB growth rate becomes lower at decreasing temperature. Hence it becomes more difficult for AOB to outcompete NOB by their growth rate and a complete NOB wash-out becomes more challenging. Also a further increase of the loading rate is no longer possible since the reactor is already operated at its limits. pH-value ranged between $8 - 8.50$ and the NH_4^+ removal degree should not fall below 50 %. However a lower nitrite accumulation cannot only be accounted to the temperature reduction since R4 did not show comparable results under similar conditions.

4.4   R4 – Reactor performance
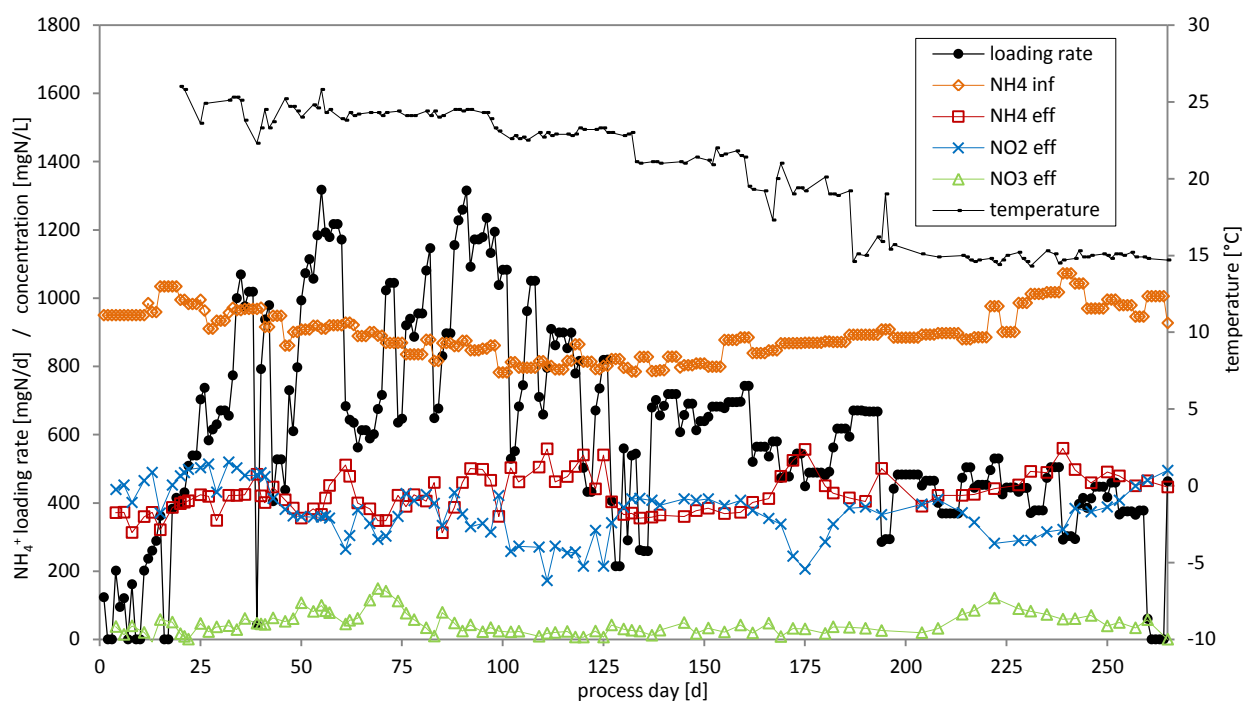
Figure 25: Reactor performance - R4
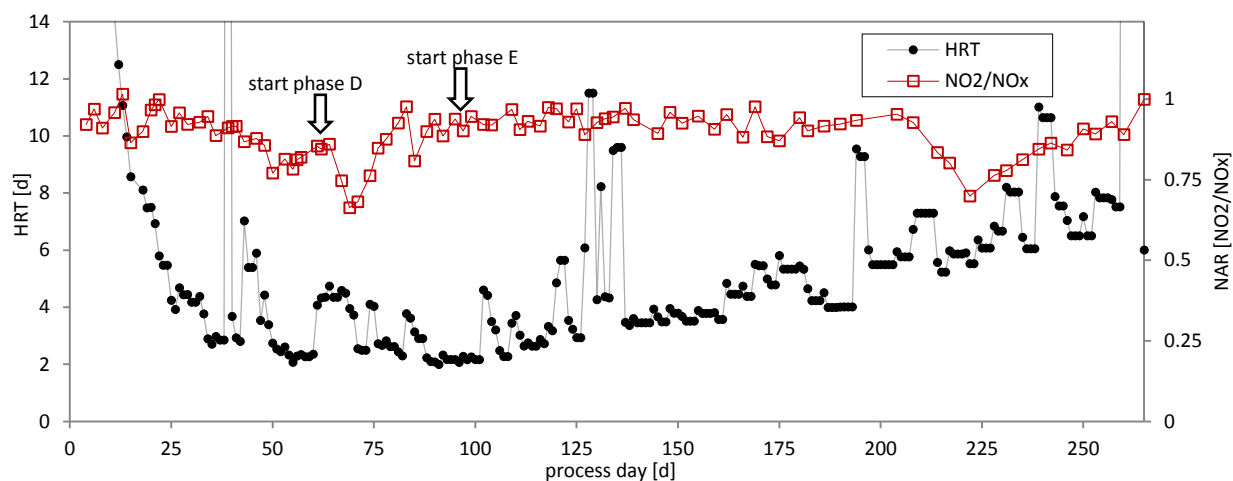
Figure 26: Nitrite accumulation ratio and hydraulic retention time over time - R4
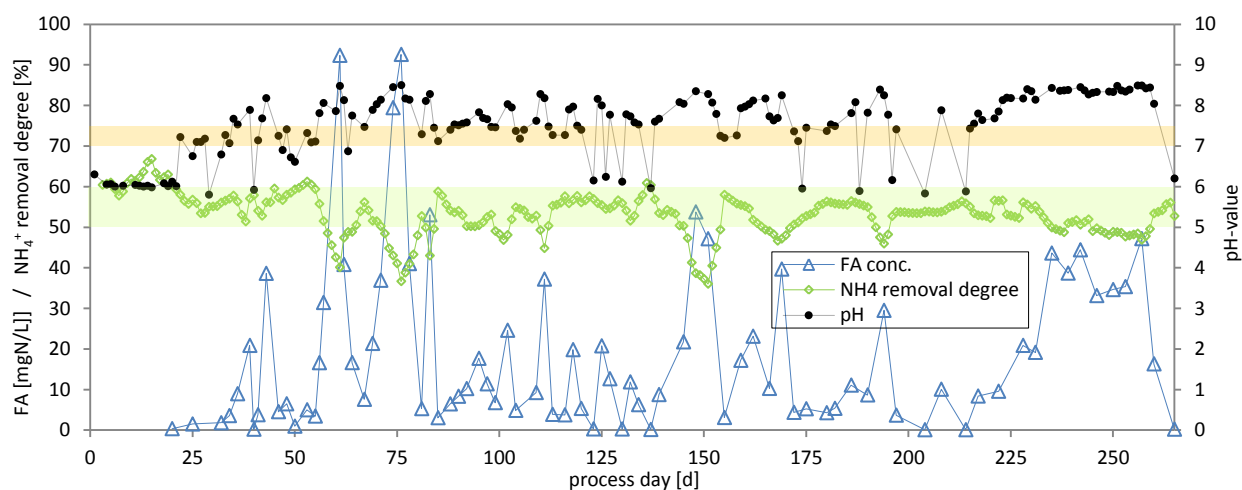
Figure 27: FA conc. / NH4 removal degree / pH-value over time - R4
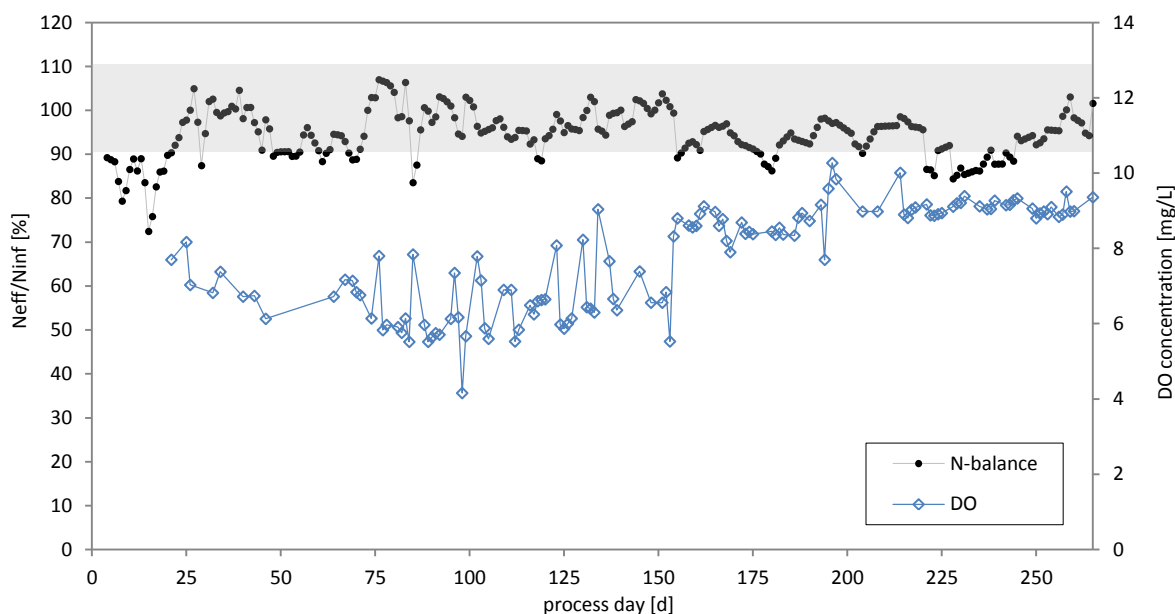
Figure 28: N-balance and DO concentration over time - R4

Figure 25 shows the reactor performance of R4. Like in R3, the effluent NH_4^+-N concentration is high from the beginning on, since the effluent of R1 was used for the inoculation and ammonium does not need time to accumulate in the system. Up to process day 90 the effluent NH_4^+-N concentration varies in a range between 350 – 450 mgN/L. In this range the system shows a stable conversion performance with an average NH_4^+ removal degree ranging between 50 – 60 %. Only exceptions are cloggings with a lower concentration. On process day 61 and 62 an overloading caused an increased NH_4^+-N concentration in the effluent of around 480 – 510 mgN/L. NH_4^+ removal degree dropped down to 44 %. On process days 43 and 46, like in R1, high pH-values were misinterpreted as an overloading although NH_4^+-N concentration in the effluent did not indicate any. On the other hand between process days 92 – 97 an overloading occurred, which was not seen as such. The effluent NH_4^+-N concentration climbed up to 500 mgN/L and the NH_4^+ removal degree decreased down to 41 %. Between process days 97 – 102 the system again recovered. Since no measures were performed another overloading occurred for a long period of about 25 days, between process days 102 – 127. Effluent NH_4^+-N concentration ranged between 460 – 560 mgN/L and NH_4^+ removal degree fell down to a minimum of 32 %. The problem during that time was that the loading rate was not reduced, since the intention was to keep the operation modes of R3 and R4 as similar as possible. HCl was dosed on a daily basis for about 20 days up to process day 120. No recovery of the system was achieved

during the whole time. Only by process day 127, when loading rate was finally reduced, the system was able to recover. Up to process day 169 NH_4^+-N concentration again remained stable and removal degree ranged between 50 – 60 %. Between process days 172 – 180 another overloading occurred when temperature was decreased to about 19 °C, but the system also recovered on its own. Between process days 180 – 228 conversion performance remained stable and NH_4^+-N concentration stayed below 450 mgN/L, except for process day 194, where a short overloading occurred. As of process day 228 the effluent NH_4^+-N concentration began to exceed 450 mgN/L on a regular basis, since also the influent NH_4^+-N concentration began to increase. pH-value from that day on also remained above pH 8, while removal degree remained at an tolerable value of above 50 %. Only on process day 175 another overloading occurred and removal degree dropped down to 45 % for one day.

Table 7: Temperature profile of R4

process day	temperature	NH_4^+-loading rate	comment
56 – 96	24.3 °C ± 0.4 °C	-	-
97 – 132	23.0 °C ± 0.4 °C	800 - 900 mgN/d	-
133 – 160	21.3 °C ± 0.7 °C	approx.700 mgN/d	-
161 – 186	19.3 °C ± 0.8 °C	450 – 550 mgN/d	except for process day 167 (17.3 °C), process day 168 (20.0 °C), process day 169 (21.0 °C)
187 – 265	15.0 °C ± 1.2 °C	350 – 500 mgN/	except for process day 195 (19.0 °C)

Table 7 shows the temperature profile of R4, with corresponding ammonium loading rates. Also in R4, temperature remained uncontrolled up to process day 46.

Loading rate in R4 steadily increases up to process day 35 up to 1070 mgN/d and remains at a level around 1000 mgN/d between process days 34 – 38. Between process days 38 – 43 R4 experiences some feed fluctuations. Due to a misinterpretation of an overloading feed was adjusted on process day 43 to about 400 mgN/d. Up to process day 55 loading rate was again slowly increased up to 1200 mgN/d between process days 54 – 60. Due to an overloading on loading rate was again reduced between process days 61 – 70 and ranged between 550 – 700 mgN/d. Between process days 71 – 88 loading rate experienced frequent

fluctuations in loading rate varying between 650 – 1100 mgN/d. Between process days 88 – 137 loading rate was steadily reduced, while undergoing frequent cloggings and periods of low loading rate for system recovery, due to overloadings. Loading rate is reduced from about 1200 – 700 mgN/d. Between process days 137 – 161 loading rate remains very stable around 700 mgN/d and a temperature of around 21 °C. Loading rate between process days 161 – 186 ranges between 450 – 600 mgN/d. Temperature during this period amounts to about 19 - 20 °C. Between process days 187 – 193 loading rate remains steady at around 650 mgN/d, when immediately after it had to be reduced, due to overloading. For the rest of the investigation period up to process day 265 loading rate ranges between 300 – 500 mgN/d, depending on the systems performance. Temperature during that time amounts to about 15 °C.

Up to process day 43 R4 showed very similar behaviour to R3. When NAR in R3 decrease NAR in R4 was still at a value of around 0.90. Like in R3 a high pH-value in R4 on process day 43 was wrongly interpreted and loading rate was reduced to about 500 mgN/d. However, unlike in R3, this measure did not show the desired results of a system recovery and pH-value on process day 46 was still as high as 3 days earlier. For R3, this measure was more successful and pH the following 10 days remained below 7.25. Decreasing NAR was the consequence. In R4 anyhow, pH was most of the time above 7.70 which might have caused a lower NOB recovery, due to high FA concentrations. When NAR in R3 dropped down to 0.30 in R4 during the same time, NAR remained above 0.80.

Due to high pH-values on process days 60 – 62 loading rate was again reduced to about 600 mgN/d by process day 70. pH, as a response, decreased as well until process day 70 and reached a level of around pH 7.50. Also NAR became lower and dropped down to 0.70 by process day 70. Only through increasing the loading rate up to about 1000 mgN/d, NAR again increased and reached a value of 0.98 by process day 83. From that day on both reactors again showed similar behaviour and NAR in R4 remained at a level above 0.90 until process day 208.

The main purpose of R4 was to support the results from R3. The idea was to identically operate both reactors in order to prove the reproducibility of the obtained results. However, due to an external damage, which led to leakage of the reactor vessel on process day 97 the old vessel had to be replaced by a new one. It was discovered, that a high amount of biofilm

had built up on the reactor walls and bottom. Biofilm was removed from the wall and ended up as a high amount of well mixed sludge in the bulk liquid. Process day 97 (or process day 157 for R1 and R2) was also the beginning of phase E, when biofilm on the reactor walls were removed from all of the 4 reactors on a daily basis. The high amount of sludge in bulk liquid phase, led to a higher conversion performance for a short while. Sludge was better mixed and received more substrate and oxygen. However, due to a low HRT of about 2 days the sludge was also quickly removed from the system by discontinuous sludge withdrawal in phase E and sludge was no longer able to accumulate in the reactor. A steady decrease of the conversion performance was the consequence, which ended in an overloading of the system. NH_4^+-N concentration in the effluent slowly increased for the period between process days 102 – 120 and pH-values were above pH 8 for almost the whole period. Since the loading rate was not reduced and only a regular dosage of HCl for a very long period was carried out, the system was able to recover only very slowly. Due to high pH-values nitrite accumulation however remained high. In R3 the reduction of the loading rate was more successful and no overloading occurred.

Between process days 123 – 180 R3 and R4 showed again very similar behaviour regarding the operation mode, as well as the NH_4^+ conversion and the nitrite accumulation, except for the minor overloading in R3 between process days 148 – 151. On process day 180, when NAR in R3 started to decrease, nitrite accumulation in R4 remained stable. R4 on the other hand experienced a major overloading between process days 172 – 175. Nitrite accumulation remained high, due to high pH-values. The reason for the sudden overloading is difficult to explain, since operation mode for R3 and R4 were almost identical. Maybe if in R3 no clogging had occurred, R3 would have also experienced an overloading, like R4. However, between process days 165 – 175 frequent dosage of HCl was carried out in order to reduce pH-values recover the system. On process day 187 the temperature was also reduced in R4 to about 15 °C. NAR did not fall, which proves that partial nitritation can also be achieved for lower temperatures. But also in R4 the lower temperatures caused a lower bacterial activity and loading rate had to be adapted from about 700 mgN/d to 300 mgN/d. NAR however remained high. Nevertheless on process day 197 the feeding and withdrawal mode was also changed in R4, due to winter holidays and like in R3 and sludge accumulation was promoted. Since NAR was still high during that time, initially no effect upon the nitritation performance was discovered. Only by process day 214, when the withdrawal

mode was already switched from continuous back to discontinuous, a small drop in NAR is noticed. NAR decreased from about 0.90 – 0.70 by process day 222. Remarkable for this period is that pH-value for this whole period never fell below 7.81. It seems like for a lower temperature range higher pH-values are required in order to maintain inhibitive effects upon NOB through FA inhibition. Taking a closer look on Eq. 17 this can also be seen for the calculations of FA. The lower the temperature becomes, the lower is the FA concentration for the system. This means that whether pH-value or NH_4^+-N concentration must increase in order to maintain the same FA level. Despite of very high FA levels, as can be seen in Figure 27, NAR only amounted to 0.70 – 0.80 between process days 222 – 235 and ranged between 0.80 – 0.90 for the period between process days 235 – 265 until the end of the investigation period.

4.5   OUR measurements

Table 8 - Table 11 show the results for OUR measurements of R1 – R4, respectively. pH-value was noted before and after measurement. Table 8 - Table 11 also contain a mean value for the temperature, which was measured during OUR determination. Additionally other relevant performance data are listed in the tables like loading rate and dissolved oxygen concentration which was measured the same day.

Table 8: OUR determination of R1

mode	pd [d]	pH before [ ]	pH after [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	OUR [mg/(L*h)]	comment
R1	87	-	-		-	-	-	
R1	93	-	-	24.9	-	1143	47.1	high sludge accumulation due to phase C
R1	114	-	-	25.4	6.5	1466	67.1	high sludge accumulation due to phase C
R1	130	-	-	26.0	6.39	1241	35.0	end of phase C
R1	138	-	-	25.7	7.5	1407	8.2	
R1	142	-	-	26.9	5.09	1897	9.8	
R1	151	7.85	7.96	23.9	5.11	1769	5.4	
R1	156	7.78	7.9	22.3	5.57	1736	8.6	
R1	191	7.76	8.02	23.7	6.62	1021	19.3	
R1	213	7.79	-	23.0	6.5	979	37.5	
R1	220	-	-	22.7	7.88	1083	36.5	
R1	241	7.77	7.86	20.7	7.53	1092	16.8	
R1	253	7.63	7.82	20.4	8.09	980	10.8	
R1	276	7.68	8	21.0	6.95	1077	98.4	high sludge accumulation due to winter holidays
R1 NH4	276						85.8	
R1 ATH	276						5.8	OUR ATH / OUR normal = 5.8 %
R1	297	7.78	-	20.7	7.5	1150	53.7	
R1 NH4	297						49.1	
R1 ATH	297						3.9	OUR ATH / OUR normal = 7.2 %
R1	306	8.3	8.27	19.7	7.99	1020	42.3	
R1 NH4	306						43.6	
R1 ATH	306						5.3	OUR ATH / OUR normal = 12.5 %
R1	318	8.36	8.32	-	7.23	1265	53.7	
R1 NH4	318						52.3	
R1 ATH	318						5.0	OUR ATH / OUR normal = 9.3 %

Table 9: OUR determination of R2

mode	pd [d]	pH before [ ]	pH after [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	OUR [mg/(L*h)]	comment
R2 with carrier	87	-	-	26.3	-	1538	174.2	
R2 w/o carrier	87			26.2			91.9	
R2 with carrier	93	-	-	26.8	-	3642	227.4	
R2 w/o carrier	93			27.0			59.2	
R2 with carrier	114	-	-	26.1	5.3	2490	180.1	
R2 w/o carrier	114			26.0			91.0	
R2 with carrier	130	-	-	25.6	5.27	3776	191.8	
R2 w/o carrier	130			25.5			99.2	
R2 with carrier	138	-	-	25.2	5.66	2850	180.0	
R2 w/o carrier	138			25.1			90.2	
R2 with carrier	142	-	-	25.1	5.01	3530	248.6	
R2 w/o carrier	142			25.0			113.1	
R2 with carrier	151	7.76	-	23.5	5.2	3309	247.6	OUR carrier / OUR total = 79 %
R2 w/o carrier	151			22.6			51.1	no more biofilm abrasion of carriers
R2 with carrier	156	7.67	7.82	22.2	5.82	3107	269.6	OUR carrier / OUR total = 96 %
R2 w/o carrier	156			22.3			12.0	
R2 with carrier	191	7.62	7.85	23.2	5.98	1768	227.0	OUR carrier / OUR total = 98 %
R2 w/o carrier	191			23.2			5.4	
R2 with carrier	213	7.9	8.05	21.7	4.1	2564	281.6	OUR carrier / OUR total = 81 %
R2 w/o carrier	213			21.7			53.8	
R2 with carrier	220	-	-	22.2	6.11	2243	223.3	OUR carrier / OUR total = 92 %
R2 w/o carrier	220			22.2			18.0	
R2 with carrier	241	7.76	7.97	20.7	6.36	3052	129.1	feed bottleneck
R2 w/o carrier	241			20.4			11.9	OUR carrier / OUR total = 91 %
R2 with carrier	253	8.13	8.21	20.7	5.58	3543	269.8	OUR carrier / OUR total = 98 %
R2 w/o carrier	253			20.5			4.2	
R2 with carrier	276	7.89	8.09	20.7	5.17	3084	322.4	high sludge accumulation due to winter holidays
R2 w/o carrier	276			21.4			42.6	OUR carrier / OUR total = 87 %
R2 w/o carrier, NH4	276			20.7			29.7	
R2 with carrier, ATH	276			20.8			39.6	
R2 with carrier, ATH 2nd try	276			20.9			23.4	OUR ATH / OUR normal = 7.3 %
R2 with carrier	297	7.66	7.9	20.4	-	3331	202.0	OUR carrier / OUR total = 91 %
R2 with carrier, NH4	297			20.5			197.6	
R2 w/o carrier	297			19.7			18.2	
R2 w/o carrier, NH4	297			19.9			20.7	
R2 with carrier	306	8.2	8.21	20.9	5.74	3862	180.6	OUR carrier / OUR total = 92 %
R2 w/o carrier	306			20.9			15.0	
R2 w/o carrier, NH4	306			20.9			11.9	
R2 with carrier	318	7.84	7.91	19.8	5.54	3051	228.0	OUR carrier / OUR total = 90 %
R2 with carrier, NH4	318			19.9			170.9	
R2 w/o carrier	318			19.2			22.8	

Figure 29 shows the data for the OUR determination of R1 and R2 over time. OUR measurements were performed between process day 87 and 318. OUR for R2 is determined

with and without carrier media. Additionally OUR with the addition of ATH is determined between process days 276 – 318 for R1, while OUR with addition of ATH for R2 with carrier media was only performed once, on process day 276. Since OUR did not significantly change, when NH_4Cl was added, only values for OUR without the addition of NH_4Cl are illustrated, in Figure 29. However values for OUR with addition of NH_4Cl for each reactor can be seen in Table 8 - Table 11.
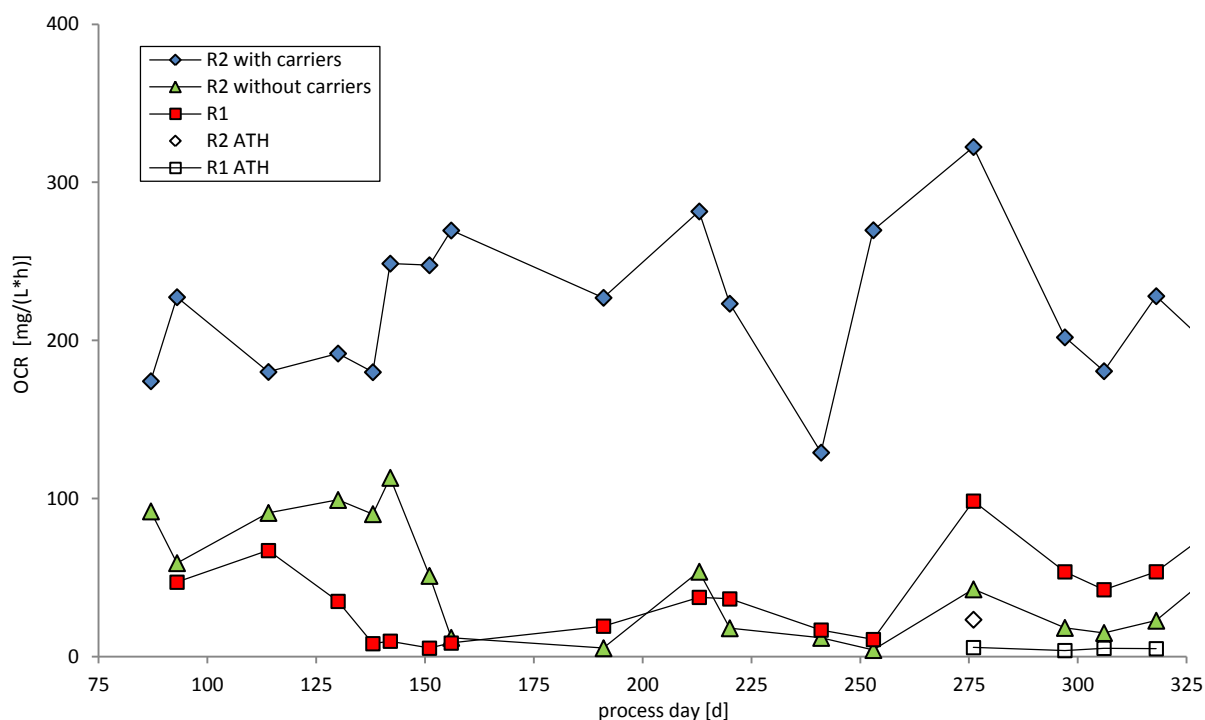
Figure 29: OUR determination of R1 and R2

OUR for R1 ranges between 5 – 100 mg/(L*h), with an overall mean value of 34 mg/(L*h) for the whole investigation period. However it has to be noted, that R1 contained a high amount of suspended solids up to process day 121, when phase D started. Especially the prior phase C led to a high amount of sludge accumulation. For this reason OUR on process day 93 and 114 was significantly higher than for the rest of the time. By process day 130 OUR already decreased to 35 mg/(L*h). Between process days 138 – 156 OUR was constantly below 10 mg/(L*h) which speaks of a low concentration of suspended solids during that time. Between process days 156 – 253 OUR remained below 35 mg/(L*h). On process day 276 OUR for R1 again increased up to almost 100 mg/(L*h). This was right after winter holidays, when a high amount of sludge accumulated, due to a change of the feeding and sludge

withdrawal mode. Between process day 297 – 318 OUR for R1 ranged between 40 – 50 mg/(L*h). Without counting in phases with a high sludge accumulation the average OUR for R1 amounts to 29 mg/(L*h).

OUR for R2 with carrier media ranges between 175 – 280 mg/(L*h) for most of the time. One lower peak can be seen on process day 241 with an OUR of 130 mg/(L*h) and a upper peak on process day 276 with an OUR of 320 mg/(L*h). According to an overall mean-value of 222 mg/(L*h) for the whole period, OUR of R2 is about 7 times higher than the one of R1. OUR of R2 without carrier media shows high values up to process day 142. However, like already explained in Chapter 4, the method for the OUR determination in R2 during that time was not representative in order to draw reasonable conclusions of the sludge distribution between bulk liquid and biofilm. The way of measuring OUR for R2 up to process day 142 led to high degree of biofilm abrasion which ended up in the bulk liquid. Afterwards the mode for OUR determination was changed. From process day 151 on, it can be seen that bacterial activity can particularly be found in the biofilm of the carriers, since OUR with carrier media is significantly higher than OUR without carriers. 80 - 98 % to the entire oxygen consumption of R2 can be attributed to biofilm, which indicates a high bacterial activity on the carriers and hence a great treatment capacity for MBBR technology treating SDE. The lower value on process day 241 was determined 2 days after the shut-down of the system, due to a feed bottleneck between process days 235 - 240. It is very likely that bacteria were still negatively affected by this measure.

As expected, OUR for R1 and R2 with the addition of ATH remains very low and almost ceases. As can be seen also in Table 8 OUR with ATH for R1 ranges between 3.9 – 5.8 mg/(L*h), which represent about 5 – 12 % of the normal OUR of R1. OUR with ATH for R2 was only determined on process day 276. OUR amounts to 23.4 mg/(L*h), which represents about 7.3 %.

Table 10: OUR determination of R3

mode	pd [d]	pH before [ ]	pH after [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	OUR [mg/(L*h)]	comment
R3	216	8.00	8.07	18.6	8.41	517	11.5	high sludge accumulation due to winter holidays
R3 NH4	216			18.4			20.5	
R3 ATH	216			18.4			4.2	OUR ATH / OUR normal = 37 %
R3	237	8.39	8.42	18.5	8.85	534	15.6	
R3 NH4	237			18.5			15.8	
R3 ATH	237			18.5			1.3	OUR ATH / OUR normal = 8 %
R3	246	7.66	7.75	19.4	-	472	16.4	
R3 NH4	246			19.0			16.8	
R3 ATH	246			18.7			1.3	OUR ATH / OUR normal = 8 %
R3	258	7.82	7.88	19.6	8.61	349	4.8	
R3 NH4	258			18.9			5.8	
R3 ATH	258			18.3			0.0	OUR ATH / OUR normal = 0 %

Table 11: OUR determination of R4

mode	pd [d]	pH before [ ]	pH after [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	OUR [mg/(L*h)]	comment
R4	216	8.23	8.23	17.4	8.81	504	22.3	high sludge accumulation due to winter holidays
R4 NH4	216			17.9			18.1	
R4 ATH	216			18.0			1.7	OUR ATH / OUR normal = 8 %
R4	237	8.48	8.43	19.6	9.04	504	8.1	
R4 NH4	237			19.2			8.0	
R4 ATH	237			19.0			0.6	OUR ATH / OUR normal = 7 %
R4	246	8.29	8.32	16.6	-	413	10.8	
R4 NH4	246			16.7			11.2	
R4 ATH	246			16.7			1.8	OUR ATH / OUR normal = 17 %
R4	258	7.64	-	16.7	9.51	377	15.1	
R4 NH4	258			16.9			17.0	
R4 ATH	258			17.0			2.1	OUR ATH / OUR normal = 14 %
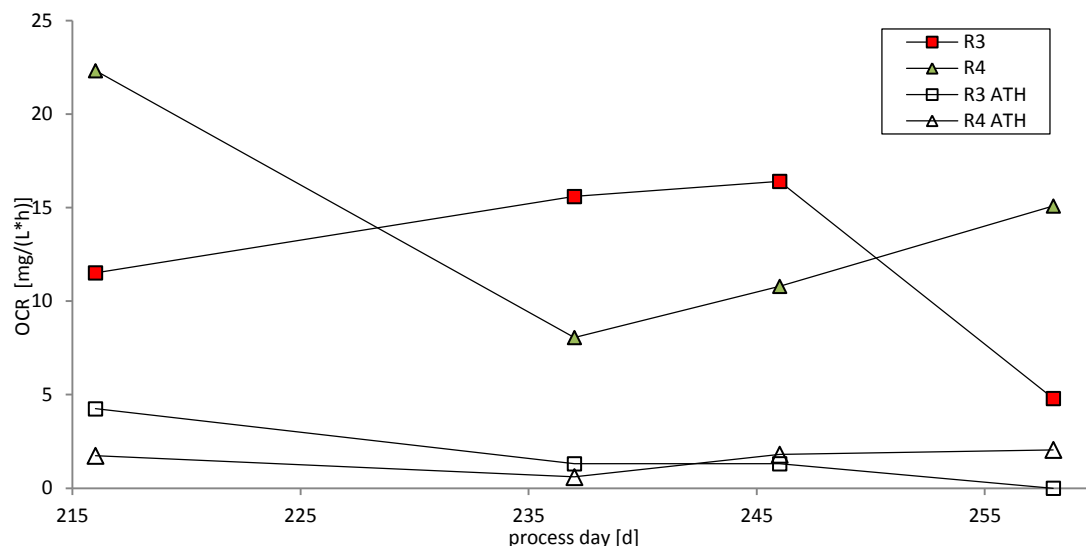
Figure 30: OUR determination of R3 and R4

All of the OUR values for R3 and R4 were determined when temperature of both reactors were already reduced to about 15 °C. However the temperature, which was measured by the oxygen sensor, shows significantly higher values. It was discovered that the oxygen sensor shows wrong values when temperature is below 20 °C. The temperature of the sludge was again measured with a different sensor after OUR determination and showed values between 15 – 16 °C. This means that the temperature did not significantly changed during measurement. OUR for R3 ranges between 5 – 16 mg/(L*h) with a mean value of 12 mg/(L*h). OUR for R4 was slightly higher with values ranging between 8 – 22 mg/(L*h) and an average of 14 mg/(L*h). The influence of the temperature can obviously be seen in the OUR's of R3 and R4. Like the loading rate also OUR for both reactors are lower compared to R1, due to a lower bacterial activity at lower temperatures.

For R3, OUR ATH ranges between 0 – 4.2 mg/(L*h). The ratio between OUR ATH to OUR normal remains below 8 %, except for process day 216, where it amounts to almost 37 %. However, this could be explained by an increased activity of NOB. NAR on that day amounts to approximately 0.30. Only AOB, but not NOB are inhibited by ATH. For this reason the oxygen uptake rate increases when NAR decreases, since the conversion of NO_2^- to NO_3^- requires additional oxygen. For the other days when OUR is determined NAR is above 0.60. OUR ATH for R4 ranged between 0.6 – 2.1 mg/(L*h). The ratio between OUR ATH to OUR normal for R4 ranges between 7 – 17 %. However NAR was above 0.80, for all of the days when OUR was measured for R4. The slightly increased OUR with ATH of 17 % cannot be explained by this theory.

4.6   N$_2$O – emission

Table 12: Measurement values for N$_2$O emission

	[d}	R1		R2		R3		R4	
		A	B	A	B	A	B	A	B
N$_2$O [ppm]	138	3.7	2.7	1.3	2.6	-	-	-	-
CO$_2$ [%]		0.0	0.0	0.0	0.0	-	-	-	-
N$_2$O [ppm]	158	13.8	10.2	19.1	18.7	-	-	-	-
CO$_2$ [%]		0.0	0.0	0.0	0.0	-	-	-	-
N$_2$O [ppm]	193 / 133	0.0	3.4	7.8	7.8	3.6	2.0	3.7	7.3
CO$_2$ [%]		0.0	1.3	1.3	1.1	1.2	0.9	1.3	1.6
N$_2$O [ppm]	214 / 154	2.2	1.5	4.1	3.9	1.1	1.8	1.2	1.6
CO$_2$ [%]		0.6	0.7	1.0	0.9	0.4	0.7	0.9	0.5
N$_2$O [ppm]	221 / 161	5.7	9.1	1.1	0.0	2.7	2.8	3.1	4.1
CO$_2$ [%]		1.0	1.5	0.7	0.0	0.5	1.1	0.8	0.7
N$_2$O [ppm]	241 / 181	3.0	2.5	5.5	5.1	1.8	2.6	0.0	0.0
CO$_2$ [%]		0.0	0.0	0.8	0.9	0.0	0.0	0.0	0.0
N$_2$O [ppm]	257 / 197	38.5	28.2	44.6	21.8	56.6	38.2	19.1	7.9
CO$_2$ [%]		1.2	1.0	2.2	0.9	2.2	1.3	0.5	0.6
N$_2$O [ppm]	278 /218	2.6	2.9	11.5	11.4	0.0	0.0	0.0	0.0
CO$_2$ [%]		0.7	0.5	1.6	1.0	0.0	0.0	0.0	0.0
N$_2$O [ppm]	288 / 228	5.7	8.8	17.8	21.4	21.4	44.9	4.1	1.9
CO$_2$ [%]		1.5	0.9	1.6	2.1	1.7	1.7	0.7	0.0
N$_2$O [ppm]	304 / 244	4.4	3.4	20.1	16.1	6.6	6.7	2.0	2.0
CO$_2$ [%]		1.1	1.2	1.9	1.6	0.8	0.7	0.7	0.6
N$_2$O [ppm]	318 / 258	5.2	6.8	11.6	10.8	4.4	6.4	1.0	1.4
CO$_2$ [%]		1.5	0.8	1.4	1.1	0.7	1.0	0.7	0.6
N$_2$O [ppm]	334 / 274	5.1	3.4	9.8	9.4	0.9	1.4	1.3	2.0
CO$_2$ [%]		1.0	1.2	1.4	1.7	0.7	0.5	0.7	0.7

Table 12 shows the measured values for the evaluation of the N$_2$O emission. Grey shaded elements show measurements, which were not considered in the calculation, since ambient air had entered the sample vial (indicated by CO$_2$ gas proportion of 0) and diluted N$_2$O content. The table shows the process days for the measurement for R1 and R2 as well as for R3 and R4.

Table 13: Evaluation of N₂0 emission factor (EF) - R1

pd [d]	pH [ ]	temp. [°C]	DO [mg/L]	load NH4 in [mgN/d]	load NH4 removed [mgN/d]	NAR [ ]	N2O ppm by volume [ppm]	air flow rate [L/h]	EF$_{N2O-N/N\ load}$ [%]	EF$_{N2O-N/N\ oxidized}$ [%]
138	6.26	25.7	7.50	1407	837	0.94	-	39.4	-	-
158	7.20	22.4	5.24	1693	888	0.91	-	42.3	-	-
193	7.22	23.6	6.87	1069	580	0.93	3.45	39.5	0.35	0.65
214	6.89	22.7	8.16	979	525	0.91	1.88	41.9	0.22	0.42
221	7.02	22.5	7.44	654	326	0.93	7.43	42.3	1.34	2.68
241	7.59	20.7	7.53	1092	556	0.90	-	84.5	-	-
257	6.77	20.7	8.70	993	492	0.73	33.38	57.2	5.34	10.78
278	6.93	20	7.52	1045	541	0.26	2.74	56.4	0.41	0.79
288	7.45	19.7	7.95	1113	475	0.39	7.24	56.1	1.01	2.37
304	7.18	19.9	7.51	1141	523	0.60	3.89	58.4	0.55	1.20
318	7.76	20.5	7.23	1265	589	0.75	6.02	58.6	0.77	1.66
334	7.66	20.9	7.12	1406	669	0.75	4.21	50.0	0.42	0.87

Table 14: Evaluation of N₂0 emission factor (EF) - R2

pd [d]	pH [ ]	temp. [°C]	DO [mg/L]	load NH4 in [mgN/d]	load NH4 removed [mgN/d]	NAR [ ]	N2O ppm by volume [ppm]	air flow rate [L/h]	EF$_{N2O-N/N\ load}$ [%]	EF$_{N2O-N/N\ oxidized}$ [%]
138	8.06	25.7	5.66	2850	1476	0.92	1.95	98.3	0.19	0.36
158	7.24	22.1	5.51	3167	1699	0.94	18.86	86.3	1.43	2.66
193	6.81	23.7	5.39	2557	1473	0.95	7.79	95.3	0.81	1.40
214	6.57	23.1	6.68	2564	1318	0.96	3.99	91.6	0.40	0.77
221	6.58	22.7	6.09	2243	1124	0.99	1.14	98.3	0.14	0.28
241	7.58	21.3	6.36	3052	1371	0.94	5.33	109.2	0.53	1.18
257	7.00	21.3	6.96	3139	1358	0.91	33.18	85.5	2.51	5.81
278	7.17	20.6	6.03	2004	1020	0.98	11.46	101.5	1.61	3.17
288	6.48	20.2	7.29	3185	1402	1.00	19.59	92.8	1.58	3.60
304	8.26	20.4	6.13	4642	1814	0.93	18.10	98.2	1.06	2.72
318	7.36	20.6	5.54	3051	1483	0.98	11.20	97.4	0.99	2.04
334	7.08	20.9	6.14	2905	1378	0.95	9.63	102.9	0.95	2.00

Table 13 to Table 16 show the evaluation of the N₂O emission factor (EF) for R1 – R4. The tables include the most relevant operation conditions (pH-value, temperature, DO, NAR) at the time of the measurement. For the N₂O gas proportion a mean value out of two samples is calculated, if both samples show no signs of dilution with ambient air (CO2 gas proportion > 0 %). One emission factor refers to the influent NH_4^+ loading rate (EF$_{N2O-N/N\ load}$), while the second emission factor refers to the amount of NH_4^+ converted in the reactor (EF$_{N2O-N/N\ oxidized}$). Evaluations of the N₂O EF were performed between process days 138 – 334 for R1 and R2 and between process days 133 – 274 for R3 and R4.

Table 15: Evaluation of N$_2$0 emission factor (EF) - R3

pd [d]	pH [ ]	temp. [°C]	DO [mg/L]	load NH4 in [mgN/d]	load NH4 removed [mgN/d]	NAR [ ]	N2O ppm by volume [ppm]	air flow rate [L/h]	EF$_{N2O-N/N\ load}$ [%]	EF$_{N2O-N/N\ oxidized}$ [%]
133	7.58	21.1	6.81	746	405	0.92	2.82	58.8	0.62	1.14
154	7.25	21.5	8.39	726	349	0.95	1.46	94.5	0.53	1.10
161	8.03	19.5	8.91	721	333	0.96	2.76	89.7	0.95	2.06
181	7.53	19.1	8.01	509	260	0.77	-	85.5	-	-
197	7.41	15.9	9.04	372	164	0.40	47.42	58.4	20.66	46.99
218	7.64	15	8.69	487	241	0.28	-	41.0	-	-
228	8.17	15.4	8.80	432	174	0.38	38.12	57.9	14.17	35.23
244	8.27	15.2	9.03	535	225	0.75	6.60	83.5	2.86	6.81
258	8.42	14.4	8.61	349	156	0.86	5.40	67.6	2.91	6.49
274	8.18	14.5	8.67	525	239	0.78	1.12	74.7	0.45	0.98

Table 16: Evaluation of N$_2$0 emission factor (EF) - R4

pd [d]	pH [ ]	temp. [°C]	DO [mg/L]	load NH4 in [mgN/d]	load NH4 removed [mgN/d]	NAR [ ]	N2O ppm by volume [ppm]	air flow rate [L/h]	EF$_{N2O-N/N\ load}$ [%]	EF$_{N2O-N/N\ oxidized}$ [%]
133	7.11	21.1	6.30	544	303	0.94	5.50	20.1	0.57	1.01
154	7.37	21.5	8.32	682	360	0.94	1.36	78.1	0.43	0.82
161	8.03	19.5	8.92	743	344	0.94	3.63	64.4	0.87	1.88
181	7.02	19	8.36	491	190	0.92	-	57.1	-	-
197	7.18	15.7	9.84	441	200	0.93	13.52	45.6	3.88	8.57
218	8.08	14.7	9.09	453	217	0.79	-	44.4	-	-
228	8.39	15.2	9.11	432	166	0.76	4.05	34.2	0.89	2.31
244	8.25	14.9	9.28	414	176	0.85	2.01	37.4	0.50	1.18
258	7.61	14.8	7.59	377	197	0.92	1.18	45.2	0.39	0.75
274	8.45	14.3	8.90	463	206	0.88	1.67	52.7	0.53	1.19

A full-scale SDE side-stream treatment over nitritation in Kirchbichl (Austria) applies almost the same method as had been applied for lab-scale experiments in the present thesis for R1, R3 and R4. Also process conditions regarding nitrite accumulation and DO concentrations are highly comparable. N2O emission was conducted with an online measurement using IR spectrometer. The measurements of the EF$_{N2O-N/N\ oxidized}$ show values between 3.6 - 4.5 %, while the lower value was measured under optimized process conditions (higher DO) (Baumgartner and Parravicini, 2018).

EF$_{N2O-N/N\ oxidized}$ for R1 amount to 0.42 - 10.78 %. However it has to be mentioned that 6 out of 9 values are below 2 %, while the outlier of over 10 % is rather doubtful. The rest of the values amount to 0.42 – 1.66 % which is also considered to be too low for SDE side-stream

treatment processes over nitritation. In R2 $EF_{N20-N/N\ oxidized}$ ranges between 0.28 − 5.81 %, while only 4 out of 12 values can be found below 2 %. However in R2 the outlier on process day 257 with an $EF_{N20-N/N\ oxidized}$ appears to be more plausible than in R1, where the factor is twice as high. The implausibility of the measurement values of process day 257/197 is further demonstrated particularly in R3, where $EF_{N20-N/N\ oxidized}$ amounts to 47 %. This would mean, that almost half of the oxidized ammonium ended up as nitrous oxide. However in R3 also the measurement of process day 228 does not seem trustworthy as $EF_{N20-N/N\ oxidized}$ amounts to 35 %. The rest of the time the emission factor ranges between 0.98 − 6.81 %, with 3 out of 8 value below 2 %.In R4 only 2 values out of 8 values for $EF_{N20-N/N\ oxidized}$ was above 2 %, while one among these two amounted to 8.57 %.

Overall it can be said, that all of the obtained results of the gas samples for all of the four reactors vary significantly, which makes it difficult to draw plausible conclusions regarding the process parameter that might have caused these highly fluctuating emission factors. In R2 probably the most trustworthy emission factors were determined since two-thirds of the obtained values were considered to be in a plausible range. In general no correlation between process conditions and emission factors can be found, neither regarding DO concentration nor nitrite concentration or ammonium loading rate during the time of measurement. Chances are high, that the method of taking gas samples was highly prone to errors. Reason could be a leaking cap, that was used to seal the reactor vessels, or a leakage of the glas vials, where gas sample was stored. Table 12 shows, that the latter occurred frequently, indicated by and CO_2 gas fraction of 0 %. Another highly sensitive parameter for the calculation of the EF is the determination of the influent air flow rate. Values for EF are dependent on a precise determination of the air flow rate. If the measured air flow rate is far from the actual air flow rate, emission factors vary significantly. A more precise method for the evaluation of the N_2O emission is required in order to study the influence of process conditions upon the N_2O emission in SDE side-stream treatment. More representative results can be obtained through IR spectrometer, since the step of gas sampling is skipped.

4.7 Suggestions for operation control

4.7.1 Start-up phase in lab-scale

In a lab-scale SDE side-stream treatment plant the initial discontinuous feeding mode showed to effectively support an increasing nitrite accumulation during start-up phase. The addition of a high amount of substrate in a very short time caused a rapid increase of the pH-value, which led to FA inhibition of NOB on a daily basis. This mode was applied since the available peristaltic feeding pumps was not able to apply a low feeding rate in order to avoid an overload in the start-up phase, when bacteria are still growing and accumulating. Increasing nitrite accumulation was this way highly supported in all of the four reactors.

For the switch to continuous feeding mode it is recommended to start earlier and to directly use undiluted feed, as applied in R3 and R4. The problem when diluting feed with effluent is the recirculation of sludge and bacteria into the system that actually needs to be washed out. This way crucial parameters like the control of the sludge age cannot sufficiently be quantified and evaluated. In R3 and R4 discontinuous feeding mode with undiluted feed was applied after 21 days of start-up, whereas in R1 and R2 this happened after 50 days. This way meaningful results can be obtained significantly earlier.

In any case, the control of NOB inhibition through high FA levels appears to be crucial, particularly in start-up phase, where loading rates are still low and a sufficient wash-out rate of NOB cannot be ensured. In almost all of the four systems nitrite accumulation decreased during start-up phase, as soon as pH-values were not high enough and sufficient FA inhibition of NOB was not achieved. High and constantly increasing loading rate is therefore crucial in order to promote nitritation. Another very crucial parameter, especially in lab-scale is the control of the sludge age, with whether improved sludge withdrawal or by applying discontinuous sludge discharge from the beginning. An accumulation of sludge changes the overall reactor performance and the values of the required HRT in suspended growth systems at given temperatures are not representative.

Finally the contribution of a biofilm upon the reactor wall appears to significantly contribute to the reactor performance in lab-scale since the ratio of the wall surface area to reactor

volume is much higher in lab-scale compared to full-scale. Control of the biofilm on the wall is therefore essential in lab-scale.

4.7.2 Impact of HRT/SRT

Overall it can be said that the influence of HRT proved to be a considerable parameter for suspended growth systems in SDE side-stream treatment, regarding the maintenance of a stable nitrite accumulation. Nevertheless the main reason for this is linked to an efficient control of the sludge age and the concentration of suspended solids. It is important that HRT equals SRT in order to achieve an efficient NOB wash-out. An effective sludge discharge is therefore essential. In many cases nitrite accumulation decreased when sludge age became higher and vice versa.

The first major recovery of nitrite accumulation in R1 was caused by a reduction of HRT from about 4 to 2.5 days at a temperature of 24.8 °C. The increase of NAR was very fast (within 7 days of HRT at 2.5 days, NAR from 0 to 0.69) and showed to be a very effective tool for a targeted NOB wash-out. No indication of FA inhibition can be seen during this time (maximum FA concentration amounted to 2.81 mgN/L). An influence of FA inhibition can be ruled out in this case. However during this time HRT and SRT were yet not equal, due to the withdrawal mode which led to sludge accumulation. However the importance of HRT can also be seen for other periods where HRT is equal to SRT and FA inhibition does not contribute to a nitrite accumulation. In R1 a NAR of about 0.90 was achieved at a HRT ranging from 1.5 – 1.7 days at temperature ranging between 22 – 24 °C. Another period of 4 days however shows a stable nitritation for even lower HRT of 2.2 – 2.4 days at a temperature of 23 – 24 °C with a NAR of 0.90 – 0.95. Stable nitrite accumulation (NAR > 0.90) was also achieved for 6 days with HRT ranging between 2.4 – 2.6 days at a temperature ranging between 22 – 22.5 °C and a FA concentration below 7 mgN/L. Decreasing NAR is observed at HRT between 2.7 – 2.8 days and temperature at around 20.5 °C and FA concentration below 2.61 mgN/L. NAR decreased within 4 days from 0.92 to 0.61.

4.7.3 Impact of FA

FA inhibition is especially important, when nitrite accumulation is at a very low level. On other hand FA inhibition is no longer required, as soon as HRT is low enough and efficient NOB wash-out is achieved. As it can be seen in the previous chapter, FA inhibition did not contribute to nitrite accumulation for certain periods.

First decline of NAR in R1 can most probably be attributed to a low FA inhibition of NOB. Between process days 71 – 92 a low loading rate led to a low pH-value and FA inhibition of NOB decreased. During this time HRT was also rather high and NOB wash-out is not achieved, therefore high FA levels are required. However it is difficult to evaluate inhibitive FA threshold values for NOB inhibition, since most of the time an increase of the loading rate is required, which is again coupled with the HRT. The influence of decreasing HRT can therefore not be ruled out. Only when loading rate and HRT remain constant and FA concentrations increase due to increasing pH-values an impact of FA inhibition can be affirmed. This occurs for example, when sludge is more effectively withdrawn from a reactor and the NH_4^+ conversion performance of a reactor decreases. As a consequence pH-values increase and FA levels increase as well, while HRT remains constant. In R1 this occurred after winter holidays when sludge withdrawal was switched from continuous back to a discontinuous withdrawal mode. Immediately after winter holidays HRT of R1 ranged between 2.5 – 2.6 days. pH-value after this period however was comparatively low, due to the high amount of sludge that has accumulated in the system during this period. Also NAR decreased down to 0.07 at this time. Enhanced sludge withdrawal showed its effect, the NH_4^+ conversion performance decreased and pH-value again increased up to pH > 8. FA level for this reason also increases and NAR again increased. However it still has to be noticed that also a more effective NOB wash-out was achieved when the switch of the withdrawal mode was performed. This could have also been the reason for increasing NAR. Still it can be said that nitrite accumulation almost never decreases when FA inhibition of NOB can be ensured, irrespective of the HRT of the system.

In R1 threshold values for an AOB inhibition through FA can be seen for a concentration of 25 - 47 mgN/L, which led to a decreasing NH_4^+ removal degree down to 48 %. An even stronger inhibition can be observed for a FA concentration of 72 mgN/L, which led to a NH_4^+ removal degree of 36 %, instead of the desired 50 – 60 %. FA concentration of 18 mgN/L led

to a decreasing NH_4^+ removal degree down to 51 %. In R2 the lowest FA concentration to show AOB inhibition was at 18.5 mgN/L, causing an NH4+ removal degree of 45 %. In R3 a constantly high FA concentration ranging between 33 – 47 mgN/L for about 10 days caused a slightly decreasing NH_4^+ removal degree down to 47 %. On the other hand an even stronger inhibition is observed in R3 at an earlier stage at FA values of 54 mgN/L causing NH4+ removal degree of 36 %. In R4 however a FA concentration between 34 – 61 mgN/L for about 10 days also led to a NH4+ removal degr NH_4^+ removal degree of 47 %. During the same time however, when FA concentration was constant at about 60 mgN/L for 4 days, NH_4^+ removal degree even recovered from 45 – 53 %. Overall it can be said that it is difficult to suggest a final FA threshold values that leads to AOB or NOB inhibition, from the results obtained in this study.

4.7.4 Impact of temperature

Impact of the lower temperatures regarding the nitritation performance was studied for suspended growth systems. For full-scale SDE side-treatment this becomes important in winter season with decreasing temperatures. Results of this thesis confirm that stable nitritation can also be achieved at low temperatures down to 15 °C. However R3 reveals that once NAR decreases it becomes more challenging to regain a stable nitrite accumulation, even at high FA levels and low HRT. In R3 NAR decreased down to 0.20 and required 30 days to increase NAR up to 0.80. FA concentration during this time was constantly above 10 mgN/L and even reaches FA concentrations of 47 mgN/L. In R4 NAR only decreases down to 0.70 and regaining the prior NAR level > 0.90 was achieved more easily. Along with the temperature also loading rate decreases due to lower growth rate of the microorganism.

4.7.5 Operation strategies for MBBR

R2 showed a very high potential for SDE side-stream treatment. Compared to CSTR, MBBR was able to treat up to 3 times the amount of SDE than CSTR, while still meeting a high NH_4^+ removal degree. R2 also proved to be far less susceptible regarding nitrite accumulation. Once a certain amount of biofilm had built up on the carrier media by process day 131, nitrite accumulation was no longer negatively affected by fluctuating operation modes.

Neither moderate pH-values, nor fluctuating loading rates were able to negatively impact the performance of R2 after a certain time of biofilm establishment.

However it has to be mentioned that before achieving a period of stable nitritation, nitrite accumulation remained unstable between process days 66 – 108, for a period of over 50 days. It is assumed that NOB had attached to the carrier media and NOB wash-out was not achieved, even at very low HRT of 1.2 – 1.8 days. Only between process days 94 – 103, high nitritation was achieved. R2 during this time experienced a shock-loading, which even led to an overloading of the system. The attached NOB were probably highly inhibited during this time and were not able to contribute to the conversion process. However, NOB were still in the system. When NH_4^+ loading rate was again reduced, NAR rapidly decreased, indicating a fast recovery of NOB activity. After this, between process days 101 – 121 loading rate was again steadily increased, pH-values were high and FA inhibition was highly promoted. However nitrite accumulated only slowly. Even though NOB inhibition was this way partly achieved, a complete wash-out took place only slowly, since a high amount of NOB had accomplished to attach on the biofilm. By creating unfavourable conditions however it was probably possible to displace NOB by AOB on the carriers and to create an ideal biofilm for achieving nitrite accumuluation. Results that were obtained after this period of biofilm formation support this assumption.

5   Conclusions and Outlook

In this thesis the technical application of two different treatment technologies (Continuously-Stirred-Tank-Reactor and Moving-Bed-Biofilm-Reactor) for SDE side-stream treatment were studied. Main focus lies in the operation strategies for achieving a stable nitritation performance, as it harbors a high potential for energy saving in a 2-stage WWTP.

The study reveals that in suspended growth systems the control of sludge age and FA inhibition proved to be an effective parameter in order to achieve nitrite accumulation. The control of the sludge age is based on different bacterial growth rates of AOB and NOB. This way NOB wash-out can be achieved. FA inhibition is based on different threshold values for AOB and NOB, which allows inhibition of NOB, while restricting AOB only partly. Moreover a stable partial nitrition is achieved in CSTR down to a temperature of 15 °C. However, once nitrite accumulation is low at low temperatures, NOB wash-out becomes more difficult to achieve. At lower temperatures the difference of the bacterial growth rates of AOB and NOB shrink.

MBBR proved to be a capable method for SDE side-stream treatment. MBBR managed to treat up to 3 times the amount of SDE compared to CSTR. Moreover nitrition in MBBR was more stable and showed lower susceptibility towards changing operation modes. When biofilm was first noticed nitrite accumulation decreased and was unstable for more than 50 days. As soon as an ideal biofilm had formed, nitrite accumulation was no longer negatively affected. However it is assumed that the operation conditions during biofilm formation can have significantly contributed to the performance and composition of the biofilm.

Future studies should focus on a better understanding of the biofilm composition as the present study leaves some questions open. Here, DNA and RNA based molecular techniques, as Polymerase Chain Reaction (PCR), Denaturing gradient gel electrophoresis (DGGE) or Fluorescent in situ hybridization (FISH) might allow identification and detection of AOB and NOB on the carrier media and might reveal deeper insights upon the biofilm composition in MBBR.

6   References

Abeling, U., and Seyfried, C.F. (1992). Anaerobic-aerobic treatment of high-strength ammonium wastewater - Nitrogen removal via nitrite. Water Sci. Technol. *26*, 1007–1015.

Anthonisen, A.C., Loehr, R.C., Prakasam, T.B.S., and Srinath, E.G. (1976). Inhibition of nitrification by ammonia and nitrous acid. J. Water Pollut. Control Fed. *48*, 835–852.

Bae, W., Baek, S., Chung, J., and Lee, Y. (2001). Optimal operational factors for nitrite accumulation in batch reactors. Biodegradation *12*, 359–366.

Balmelle, B., Nguyen, K.M., Capdeville, B., Cornier, J.C., and Deguin, A. (1992). Study of factors controlling nitrite build-up in biological processes for water nitrification. Water Sci. Technol. *26*, 1017–1025.

Baumgartner, T., and Parravicini, V. (2018). Decision support for finding the appropriate resource and energy optimized SDE treatment technology.

Baumgartner, T., Parravicini, V., and Valkova, T. (2016). Experience and performance data for the implementation of nitritation on a two-stage WWTP.

Boltz, J.P., and Daigger, G.T. (2010). Uncertainty in bulk-liquid hydrodynamics and biofilm dynamics creates uncertainties in biofilm reactor design. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. *61*, 307–316.

Brouwer, M., van Loosdrecht, M., and Heijnen, J.J. (1996). One reactor system for ammonium removal via nitrite (Utrecht; Zoetermeer: STOWA, Stichting Toegepast Onderzoek Waterbeheer ; Hageman Verpakkers [distr.).

Camilla, G., and Gunnel, D. (2001). Development of nitrification inhibition assays using pure cultures of Nitrosomonas and Nitrobacter. Water Res *35*, 433–440.

Castro-Barros, C., Rodriguez-Caballero, A., Volcke, E., and Pijuan, M. (2015). Effect of nitrite on the N2O and NO production on the nitrification of low-strength ammonium wastewater. Chem. Eng. J. *287*.

Cecen, F. (1996). Investigation of partial and full nitrification characteristics of fertilizer wastewaters in a submerged biofilm reactor. Water Sci. Technol. - WATER SCI TECHNOL *34*, 77–85.

Christensson, M., Ekström, S., Andersson Chan, A., Le Vaillant, E., and Lemaire, R. (2013). Experience from start-ups of the first ANITA Mox plants. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. *67*, 2677–2684.

Colliver, B.B., and Stephenson, T. (2000). Colliver BB, Stephenson T.. Production of nitrogen oxide and dinitrogen oxide by autotrophic nitrifiers. Biotechnol Adv 18: 219-232. Biotechnol. Adv. *18*, 219–232.

Desloover, J., De Clippeleir, H., Boeckx, P., Du Laing, G., Colsen, J., Verstraete, W., and Vlaeminck, S.E. (2011). Floc-based sequential partial nitritation and anammox at full scale with contrasting N2O emissions. Water Res. *45*, 2811–2821.

Ge, S., Wang, S., Yang, X., Qiu, S., Li, B., and Peng, Y. (2015). Detection of nitrifiers and evaluation of partial nitrification for wastewater treatment: A review. Chemosphere *140*, 85–98.

Gieseke, A., Bjerrum, L., Wagner, M., and Amann, R. (2003). Structure and activity of multiple nitrifying bacterial populations co-existing in a biofilm. Environ. Microbiol. *5*, 355–369.

Goreau, T.J., Kaplan, W.A., Wofsy, S.C., McElroy, M.B., Valois, F.W., and Watson, S.W. (1980). Production of NO2- and N2O by Nitrifying Bacteria at Reduced Concentrations of Oxygen. Appl. Environ. Microbiol. *40*, 526–532.

Han, D.W., Chang, J.S., and Kim, D.J. (2003). Nitrifying microbial community analysis of nitrite accumulating biofilm reactor by fluorescence in situ hybridization. Water Sci. Technol. *47*, 97–104.

Helmer-Madhok, C. (2004). Stickstoffelimination in Kläranlagen : neue und bewährte Wege. Hannover, Univ., Habil.-Schr., 2003 u.d.T.: Helmer-Madhok, Christine: Mischbiozönosen in Struktur und Funktion am Beispiel der Deammonifikation in Abwasserreinigungsanlagen.

Henze, M., Harremoes, P., Jansen, J. la C., and Arvin, E. (2002). Wastewater Treatment: Biological and Chemical Processes (Berlin Heidelberg: Springer-Verlag).

Jönsson, K. (2001). Inhibition of Nitrification in Municipal Wastewater - Sources, Effects, Evaluation and Remedies (Secretary, Water and Environmental Engineering, Lund Institute of Technology, P.O. Box 118, 221 00 LUND, SWEDEN).

Kampschreur, M.J., van der Star, W.R.L., Wielders, H.A., Mulder, J.W., Jetten, M.S.M., and van Loosdrecht, M.C.M. (2008). Dynamics of nitric oxide and nitrous oxide emission during full-scale reject water treatment. Water Res. *42*, 812–826.

Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S.M., and van Loosdrecht, M.C.M. (2009). Nitrous oxide emission during wastewater treatment. Water Res. *43*, 4093–4103.

van Kempen, R., Mulder, J.W., Uijterlinde, C.A., and Loosdrecht, M.C. (2001). Overview: full scale experience of the SHARON process for treatment of rejection water of digested sludge dewatering. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. *44*, 145–152.

Kong, Q., Zhang, J., Miao, M., Tian, L., Guo, N., and Liang, S. (2013). Partial nitrification and nitrous oxide emission in an intermittently aerated sequencing batch biofilm reactor. Chem. Eng. J. *217*, 435–441.

McQuarrie, J.P., and Boltz, J.P. (2011). Moving bed biofilm reactor technology: process applications, design, and performance. Water Environ. Res. Res. Publ. Water Environ. Fed. *83*, 560–575.

Nowak, O. (1996). Nitrifikation im Belebungsverfahren bei massgebendem Industrieabwassereinfluss (Institut für Wassergüte und Abfallwirtschaft).

Ødegaard, H. (1999). The Moving Bed Biofilm Reactor. 12.

Peng, Y., and Zhu, G. (2006). Biological nitrogen removal with nitrification and denitrification via nitrite pathway. Appl. Microbiol. Biotechnol. *73*, 15–26.

Peng, Y.Z., Li, Y.Z., Peng, C.Y., and Wang, S.Y. (2004). Nitrogen removal from pharmaceutical manufacturing wastewater with high concentration of ammonia and free ammonia via partial nitrification and denitrification. Water Sci. Technol. J. Int. Assoc. Water Pollut. Res. *50*, 31–36.

Piculell, M. (2016). New Dimensions of Moving Bed Biofilm Carriers : Influence of biofilm thickness and control possibilities (Department of Chemical Engineering, Lund University).

Pijuan, M., Torà, J., Rodriguez-Caballero, A., César, E., Carrera, J., and Perez, J. (2013). Effect of process parameters and operational mode on nitrous oxide emissions from a nitritation reactor treating reject wastewater. Water Res. *49C*, 23–33.

R Robertson, S., JC McLean, R., and Department of Biology, Texas State University, 601 University Drive, San Marcos, TX 78666, USA (2015). Beneficial biofilms. AIMS Bioeng. *2*, 437–448.

Rodriguez-Caballero, A., and Pijuan, M. (2013). N2O and NO emissions from a partial nitrification sequencing batch reactor: exploring dynamics, sources and minimization mechanisms. Water Res. *47*, 3131–3140.

Sinha, B., and Annachhatre, A.P. (2007). Assessment of partial nitrification reactor performance through microbial population shift using quinone profile, FISH and SEM. Bioresour. Technol. *98*, 3602–3610.

Strous, M., Heijnen, J.J., Kuenen, J.G., and Jetten, M.S.M. (1998). The sequencing batch reactor as a powerful tool for the study of slowly growing anaerobic ammonium-oxidizing microorganisms. Appl. Microbiol. Biotechnol. *50*, 589–596.

Svardal, K. (2005) Chemische Gleichgewichte und ihre praktische Bedeutung. W *192*, 219-246.

Tallec, G., Garnier, J., Billen, G., and Gousailles, M. (2006). Nitrous oxide emissions from secondary activated sludge in nitrifying conditions of urban wastewater treatment plants: effect of oxygenation level. Water Res. *40*, 2972–2980.

Uçkun Kiran, E., Stamatelatou, K., Antonopoulou, G., and Lyberatos, G. (2016). 10 - Production of biogas via anaerobic digestion. In Handbook of Biofuels Production (Second Edition), (Woodhead Publishing), pp. 259–301.

Villaverde, S., García-Encina, P.A., and Fdz-Polanco, F. (1997). Influence of pH over nitrifying biofilm activity in submerged biofilters. Water Res. *31*, 1180–1186.

Yamamoto, T., Takaki, K., Koyama, T., and Furukawa, K. (2006). Novel partial nitration treatment for anaerobic digestion liquor of swine wastewater using swim-bed technology. J. Biosci. Bioeng. *102*, 497–503.

Yoo, H., Ahn, K.-H., Lee, H.-J., Lee, K.-H., Kwak, Y.-J., and Song, K.-G. (1999). Nitrogen removal from synthetic wastewater by simultaneous nitrification and denitrification (SND) via nitrite in an intermittently-aerated reactor. Water Res. *33*, 145–154.

Zhang, Y., Love, N., and Edwards, M. (2009). Nitrification in Drinking Water Systems. Crit. Rev. Environ. Sci. Technol. *39*, 153–208.

Zhou, Y., Oehmen, A., Lim, M., Vadivelu, V., and Ng, W.J. (2011). The role of nitrite and free nitrous acid (FNA) in wastewater treatment plants. Water Res. *45*, 4672–4682.

7   Appendix

Table 17: Performance date R1 and R2

R1	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]
10.4	1				91		32.6	10.57	1.07					1						49.2	19.74	0.13			
11.4	2				224		13.3							2						13.3					
12.4	3				282		11.6	57.7	8.4					3						11.6	72	34.9			
13.4	4				0	####								4						####					
14.4	5				0	####								5						####					
15.4	6				0	####								6						####					
16.4	7				0	####								7						####					
17.4	8				0	####								8						####					
18.4	9				0	####								9						####					
19.4	10				109		30.0							10						30.0					
20.4	11				153		21.4							11						21.4					
21.4	12				219		15.0	83.9	28.6	0.17				12					219	15.0	98.3	62	0.34		
22.4	13				0	####								13						####					
23.4	14				0	####								14						####					
24.4	15				109	0.90	30.0							15					109	0.89	30.0					
25.4	16				109		30.0	107.3	80	0.38				16					109		30.0	116	102	0.50		
26.4	17				78		41.7							17					78		41.7					
27.4	18				153	0.89	21.3							18					153	0.89	21.3					
28.4	19	7.65	25		234		7.6	114.3	81	0.40	3.44	0.014		19	7.69	25		169		7.3	120.9	105.6	0.50	3.97	
29.4	20		25		240		7.5							20		25		284		7.0					
30.4	21		25		246		7.5							21		25		300		7.0					
1.5	22		25		253	0.78	7.5							22		25		316	0.75	7.0					
2.5	23	8.75	25		5	####		242.8	125.1	0.55	71.39	0.002		23	8.75	25		7	####		273.3	132	0.60	80.36	
3.5	24	8.12	25		0	0.81	16.4							24	8.40	25			0.80	####					
4.5	25	6.38	25		53		60.0	207.2	151.2	0.62	0.34	0.475		25	6.67	25		53		60.0	213.2	170	0.67	0.69	0.274
5.5	26	6.45	25		144		22.2							26	6.55	25		144		22.2					
6.5	27		25		0	####								27		25									

R1	pd	pH	temp.	DO	load NH4	removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA	R2	pd	pH	temp.	DO	load NH4	removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA
	[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]		[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]
7.5	28		25		0	0.79	####							28		25		0	0.78	####					
8.5	29	6.18	25		176		18.1	221.9	175	0.65	0.23	0.872		29	6.22	25		176		18.1	237.3	214	0.74	0.27	0.972
9.5	30	6.38	25		141	0.77	22.6							30	6.63	25		141	0.76	22.6					
10.5	31	6.15	25		157		20.3	241.2	204.5	0.70	0.23	1.091		31	6.35	25		157		20.3	257	240	0.76	0.40	0.809
11.5	32	6.15	25		205	0.75	7.8							32	6.34	25		201	0.73	8.0					
12.5	33	7.20	25		267		7.5	269.2	239.5	0.73	2.92	0.114		33	7.65	25		280		7.2	292.8	276	0.79	8.80	
13.5	34		25		267		7.5							34		25		278		7.3					
14.5	35		25		267	0.71	7.5							35		25		278	0.69	7.3					
15.5	36	6.80	25		276		7.7	311.8	315	0.82	1.35	0.377		36	7.32	25		290		7.4	335.6	371	0.90	4.78	0.134
16.5	37	7.67	25		267	0.66	8.0							37	7.82	25		271	0.64	7.9					
17.5	38	6.48	25		291		8.0	337.4	348	0.87	0.70	0.869		38	6.68	25		302		7.8	361.1	404	0.93	1.19	0.637
18.5	39	6.79	25		330	0.65	7.1							39	7.15	25		338	0.64	7.0					
19.5	40	6.50	25		331		7.5	354.5	421	0.97	0.77	1.004		40	6.89	25		340		7.3	359.2	436	0.98	1.92	0.424
20.5	41		25		307		8.2							41		25		317		7.9					
21.5	42		25		307	0.64	8.2							42		25		317	0.64	7.9					
22.5	43	7.18	25		209		11.3	359.5	424	0.98	3.72	0.211		43	8.09	25		215		11.0	361.5	403	1.00	28.68	0.025
23.5	44	6.52	25		282	0.63	8.4							44	7.44	25		282	0.65	8.4					
24.5	45	6.62	25		283		8.5	370.4	434	0.96	1.06	0.786		45	7.44	25		283		8.5	352	428	0.99	6.59	0.117
25.5	46		25		296	0.63	8.2							46		25		295	0.65	8.2					
26.5	47	7.63	25	7.30	296		8.2	371.4	403	0.92	10.67	0.071		47	7.66	25	8.60	295		8.2	346.4	397	0.95	10.65	0.066
27.5	48		25		296		8.2							48		25		295		8.2					
28.5	49		25		296	0.63	8.2							49		25		295	0.64	8.2					
29.5	50	6.69	25		302		8.4	369.8	409	0.88	1.25	0.630		50	6.99	25		297		8.5	359.2	425	0.94	2.41	0.328
30.5	51	6.58	25		328	0.63	8.5							51	6.94	25		336	0.63	8.3					
31.5	52	6.70	25		378		8.1	374.7	453	0.96	1.29	0.682		52	6.95	25		372		8.2	374.8	443	0.94	2.29	0.375
1.6	53	7.02	25		388	0.63	7.9							53	7.07	25		382	0.61	8.1					
2.6	54	6.83	25		364		8.5	377.1	454	0.97	1.75	0.507		54	6.95	25		348		8.8	396.1	440	0.88	2.42	0.373

R1	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
3.6	55		25		371		8.3							55		25		355		8.7					
4.6	56		25		371		8.3							56		25		355		8.7					
5.6	57		25		371	0.64	8.3							57		25		355	0.61	8.7					
6.6	58	7.29	25		480		6.4	365.3	435	0.97	4.86	0.168		58	6.80	25		456		6.8	395.2	372	0.77	1.71	0.445
7.6	59	6.91	25		643	0.61	4.8							59	6.78	25		588	0.59	5.2					
8.6	60	7.79	25	7.16	310	0.61	9.2	397.1	441	0.99	16.32	0.054		60	7.08	25	8.28	276	0.57	10.3	420.5	359	0.72	3.46	0.225
9.6	61	7.40	25		303		9.4	371.9	447	0.99				61	6.70	25		289		9.9	406.8	335	0.66	1.40	0.504
10.6	62		25		334		8.5							62		25		323		8.8					
11.6	63		25		334	0.59	8.5							63		25		323	0.60	8.8					
12.6	64	7.08	25	7.83	428		6.7	390.7	479	0.97	3.22	0.301		64	6.49	25	7.49	514		5.5	381.4	172	0.36	0.81	0.420
13.6	65	7.05	25		484	0.59	5.9							65	6.71	25		611	0.60	4.7					
14.6	66	7.07	25		589		4.8	392.1	485	1.01	3.16	0.312		66	6.50	25		361		7.9	384.5	1.33	0.00	0.84	0.003
15.6	67		25		665	0.67	4.3							67		25		238	0.58	12.0					
16.6	68	7.12	25		547		5.2	315.3	404	0.92	2.85	0.231		68	5.21	25		851		3.3	400.8	0.14	0.00	0.04	0.006
17.6	69		25		583		4.9							69		25		775		3.7					
18.6	70		25		583	0.52	4.9							70		25		775	0.59	3.7					
19.6	71	8.28	25		0		####	453.2	394	0.90	53.76	0.016		71	6.18	25		862		3.3	385.7	0.72	0.00	0.40	0.004
20.6	72	5.98	25		456	0.60	6.5							72	6.80	25		1077	0.59	2.7					
21.6	73	7.17	25.9	7.50	400		7.2	397.6	428	0.87	4.29	0.213		73	6.96	25	6.10	1074		2.7	399	44.9	0.09	2.50	0.037
22.6	74	7.15	25.9		586	0.56	4.9							74	6.85	25		1310	0.59	2.2					
23.6	75	7.27	25.9		106		29.4	417.2	289	0.58	5.65	0.114		75	7.01	25		1298		2.4	391.9	33.5	0.07	2.75	0.025
24.6	76		25.9		65		47.9							76		25		1331		2.3					
25.6	77		25.9		65	0.56	47.9							77		25		1331	0.55	2.3					
26.6	78	5.82	25.9		648		4.8	453.8	242	0.43	0.22	2.693		78	6.94	25		497		6.2	460.9	7.1	0.01	2.76	0.006
27.6	79	6.97	25.9	7.26	496	0.58	6.3							79	6.37	25	5.70	1828	0.58	1.7					
28.6	80	6.88	26.4		458		6.5	432.8	192	0.39	2.49	0.184		80	7.10	27.2		1283		2.3	429.5	24.8	0.05	4.32	0.014
29.6	81	6.72	25.5		811	0.56	3.7							81	6.52	26.2		1609	0.57	1.9					

R1	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
30.6	82	7.25			795		3.7	433.2	113	0.21				82	6.71			1537		1.9	431.9	4.6	0.01		
1.7	83				828		3.6							83				1576		1.9					
2.7	84				819	0.53	3.6							84				1576	0.53	1.9					
3.7	85	6.84	23.1	8.20	841		3.5	464.1	95	0.16	1.93	0.109		85	6.77	23.6	6.60	2575		1.2	459.3	37	0.06	1.68	0.049
4.7	86	7.17	24.2		837	0.55	3.5							86	8.02	24.8	3.97	1801	0.55	1.6					
5.7	87	7.14			682		4.0	437	84.8	0.15				87	6.80			1538		1.8	429.8	70	0.13		
6.7	88	6.85			719	0.53	3.8							88	6.46			1623	0.56	1.7					
7.7	89	6.81			676		4.1	427.5	21.3	0.04				89	5.23			1571		1.8	399	0.03	0.00		
8.7	90				709		4.0							90				1656		1.7					
9.7	91				709	0.53	4.0							91				1656	0.57	1.7					
10.7	92	6.23	24.8	6.39	1026		2.8	434.6	0.65	0.00	0.50	0.003		92	5.85	25.3	3.66	3157		0.9	400.6	0.09	0.00	0.20	0.001
11.7	93	7.20	24.9		1143	0.57	2.5							93	7.81	25.5		3642	0.50	0.8					
12.7	94	6.99	25.1	7.40	1152		2.5	415.8	147.6	0.29	2.81	0.114		94	7.81	25.9	4.30	3905		0.7	489.4	373.6	0.74	22.37	0.043
13.7	95	7.10	24.5		1229	0.58	2.4							95	8.05			4169	0.56	0.7					
14.7	96	6.94	23.4		1163		2.5	401.2	273	0.55	2.14	0.247		96	7.82	24.6		3697		0.8	426.4	466	0.90	18.22	0.054
15.7	97				1225		2.4							97				3830		0.8					
16.7	98				1225	0.54	2.4							98				3830	0.54	0.8					
17.7	99	6.86	22.1		51	0.56	56.9	447.8	401	0.69	1.81	0.451		99	5.92	22.4		160	0.52	18.2	441.6	532	0.91	0.21	5.153
18.7	100	5.81	22.6	8.17	1494	0.57	2.0	423.6	364	0.69	0.16	4.515		100	5.98	23	3.99	4658	0.44	0.6	460.8	437	0.88	0.26	3.630
19.7	101	7.28	24.3	6.96	1440		1.9	420.4	382	0.76	5.20	0.154		101	8.31	25.4	4.55	4031		0.7	543.8	318	0.87	70.41	0.012
20.7	102	7.28	23.4		1497	0.54	1.8							102	8.35	24.5		2683	0.55	1.0					
21.7	103	7.98	24.8	5.53	844		3.4	418.8	347	0.77	25.82	0.028		103	7.84	24.8	5.11	1966		1.4	413	376	0.78	18.71	0.041
22.7	104				1134		2.5							104				2137		1.3					
23.7	105				1134	0.46	2.5							105				2137	0.59	1.3					
24.7	106	8.38	26.2	4.51	910		2.8	511.2	262	0.81	80.24	0.008		106	7.89	25.9	4.66	1993		1.3	384.8	24	0.05	20.99	0.002
25.7	107	8.12	23.8	7.04	881	0.50	2.9							107	8.10	22.6	6.00	1556	0.56	1.7					
26.7	108	7.99	22.8		685		3.9	433	310	0.80	23.79	0.025		108	7.64	23.2		2279		1.2	379.4	13	0.03	9.83	0.002

R1	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
27.7	109	8.04			1493	0.54	1.8							109	8.06	22.7		1785	0.49	1.5					
28.7	110	7.84	23.2		1407		1.9	418.4	306	0.72	16.96	0.035		110	8.08	23.8		2032		1.3	455.2	52	0.13	32.60	0.003
29.7	111				1386		2.0							111				2092		1.3					
30.7	112				1386	0.55	2.0							112				2092	0.49	1.3					
31.7	113	8.14	24.9	6.35	1143		2.4	408.4	286	0.72	35.83	0.016		113	8.06	25.8	3.89	1930		1.4	460.8	88	0.23	36.15	0.006
1.8	114	7.16	25.4	6.50	1466		1.9							114	7.60	25.5	5.30	2490	0.52	1.1					
2.8	115	7.14	26.7	5.88	1723		1.6				4.18	0.137		115	8.06	27	4.30	2819	0.47	1.0	437.4	87	0.22	37.14	0.005
3.8	116	7.38	27	4.75	1714	0.59	1.6				7.21	0.074		116	8.23	27.6	3.69	2497	0.43	1.1	486	123	0.35	61.34	0.005
4.8	117	7.59	27.8	5.24	1523		1.8	376	236	0.51	11.98	0.043		117	8.25	28.4	3.46	2582		1.1	515	153	0.45	71.19	0.006
5.8	118				1572		1.8							118				2666		1.0					
6.8	119				1572		1.8							119				2666		1.0					
7.8	120	6.25		7.55	1524	0.51	1.8							120	7.80		4.05	2393	0.42	1.2					
8.8	121	8.00	26.6	4.86	1412	0.54	2.0	447.8	281	0.72	32.54	0.020		121	8.18	26.8	3.71	1742	0.53	1.6	532.2	171	0.58	57.53	0.008
9.8	122	7.75	27.2	2.66	1348		2.1	422.2	322	0.74	18.46	0.041		122	7.91	27	4.20	1857		1.5	436.2	249	0.62	26.77	0.022
10.8	123	7.42	28.9	4.18	1454	0.52	1.9							123	6.72	28.4	4.91	2198	0.59	1.3					
11.8	124	7.88	27.5	4.63	16		####	446.6	353	0.77	26.54	0.033		124	7.26	27.2	4.80	2072		1.3	378.8	310	0.66	5.49	0.122
12.8	125				0		####							125				2259		1.2					
13.8	126				0		####							126				2259		1.2					
14.8	127	6.07	23.4	8.32	1219		2.2							127	6.79	24	6.94	3229		0.8					
15.8	128				1245	0.55	2.2							128				3298		0.8					
16.8	129	7.41	24.8	6.76	1194		2.2	404	370	0.72	6.96	0.109		129	6.17	25.1	7.68	3574		0.7					
17.8	130	7.46	26	6.39	1241		2.2							130	7.93	25.7	5.27	3776	0.50	0.7					
18.8	131	6.91	26.6	6.02	1538		1.7							131	8.02	26.3	5.18	2619		1.0	448.4	348	0.87	33.36	0.024
19.8	132				1571		1.7							132				2675		1.0					
20.8	133				1571	0.55	1.7							133				2675	0.54	1.0					
21.8	134	6.00	24.9	7.96	1408		1.9	394	436	0.79	0.27	3.293		134	6.16	24.3	7.81	1469		1.8	396.8	451	0.83	0.38	2.395
22.8	135			5.00	1496	0.48	1.7							135				1473	0.55	1.8					

R1	pd	pH	temp.	DO	load NH4	NH4 removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA	R2	pd	pH	temp.	DO	load NH4	NH4 removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA
	[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]		[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]
23.8	136	8.03	25.9	5.18	1683		1.5	452.6	409	0.90	33.50	0.028		136	6.42	25.4	7.22	3258		0.8	393.8	452	0.88	0.73	1.283
24.8	137	8.01	25.8	5.47	1152	0.54	2.2							137	8.12	25.5	5.59	2775	0.47	0.9					
25.8	138	6.26	25.7	7.50	1407		1.8	382	465	0.94	0.50	1.892		138	8.06	25.7	5.66	2850		0.9	442.6	399	0.92	34.49	0.026
26.8	139				1538		1.6							139				3086		0.8					
27.8	140				1538	0.54	1.6							140				3086	0.48	0.8					
28.8	141	6.02	26.67	7.66	1786		1.5	386.2	454.4	0.96	0.31	3.132		141	6.14	26.5	7.65	3334		0.8	436.6	456	0.94	0.46	2.396
29.8	142	7.79	26.9	5.09	1897	0.50	1.4							142	7.96	26.6	5.01	3530	0.49	0.7					
30.8	143	7.89	26.7	5.25	1615		1.5	435.2	422	1.00	25.05	0.039		143	8.03	26.5	5.01	2921		0.8	446.4	392	1.00	34.39	0.027
31.8	144	7.90	25.4	5.57	1686	0.50	1.5							144	7.82	25.2	5.16	3048	0.56	0.8					
1.9	145	7.98	26.6	5.74	1630		1.6	409.4	373.2	0.92	28.49	0.028		145	7.24	26.3	5.30	3033		0.9	355.8	400.8	0.93	4.63	0.168
2.9	146				1650		1.6							146				3099		0.8					
3.9	147				1650	0.59	1.6							147				3099	0.56	0.8					
4.9	148	7.12	23.2	5.70	1668		1.5	356.6	396	0.91	2.83	0.238		148	7.32	23.2	5.44	3018		0.9	382.8	434.4	0.93	4.80	0.164
5.9	149	7.23	23.7	4.97	1748	0.55	1.5							149	7.46	23.4	4.83	3155	0.55	0.8					
6.9	150	7.35	22.9	5.44	1696		1.5	384.8	404.4	0.96	5.05	0.144		150	7.24	22.7	5.39	3169		0.8	384.6	441.6	0.97	3.88	0.204
7.9	151	7.57	23.9	5.11	1769	0.54	1.5							151	7.45	23.8	5.20	3309	0.55	0.8					
8.9	152	7.57	23.2	5.21	1456		1.7	400.8	373.2	0.90	8.86	0.079		152	7.32	22.7	5.23	2941		0.9	391.2	403.2	0.91	4.73	0.155
9.9	153				1562		1.6							153				3171		0.8					
10.9	154				1562	0.57	1.6							154				3171	0.58	0.8					
11.9	155	5.95	22.5	8.03	1656		1.5	360.4	424.8	0.93	0.19	3.831		155	6.86	22.2	5.86	3189		0.8	356.4	424.8	0.95	1.45	0.476
12.9	156	7.35	22.3	5.57	1736	0.56	1.5							156	7.17	21.9	5.82	3107	0.56	0.8					
13.9	157	7.02	21.8	6.00	1605		1.6	370.8	411.6	0.87	2.12	0.323		157	7.06	21.6	5.56	3002		0.9	375.4	435.6	0.92	2.31	0.313
14.9	158	7.20	22.4	5.24	1693	0.57	1.5							158	7.24	22.1	5.51	3167	0.57	0.8					
15.9	159	6.87	22.4	6.44	1451		1.6	370.2	414.4	0.96	1.56	0.452		159	7.09	22.1	5.15	2560		0.9	370.4	432.6	0.96	2.54	0.286
16.9	160				1509		1.6							160				2622		0.9					
17.9	161				1509	0.53	1.6							161				2622	0.56	0.9					
18.9	162	7.04	19.9	6.34	1301		1.9	368.2	380.8	0.82	1.91	0.300		162	6.84	19.6	6.07	2947		0.8	342.8	425.6	0.93	1.10	0.535

R1	pd	pH	temp.	DO	load NH4	NH4 removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA	R2	pd	pH	temp.	DO	load NH4	NH4 removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA
	[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]		[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]
19.9	163	7.77	21.8	5.56	1397	0.57	1.7							163	7.68	21.3	5.29	3195	0.45	0.8					
20.9	164	5.88	21.8	4.74	1230		1.9	346	411.6	0.91	0.14	4.440		164	7.89	21.8	8.18	3022		0.8	449.4	348.6	0.95	18.46	0.037
21.9	165	7.10	22	4.88	1288		1.9							165	7.78	21.8	5.67	3196		0.7					
22.9	166	6.36	21.5		1223		2.0							166	7.75	22		2575		0.9					
23.9	167				1238		1.9							167				2467		1.0					
24.9	168				1238	0.55	1.9							168				2467	0.57	1.0					
25.9	169	5.97	22.6	8.15	1689		1.4	355.6	421.4	0.98	0.19	3.620		169	5.95	23.3	8.16	2808		0.9	339.6	455	0.97	0.18	4.018
26.9	170	7.51	22.8		1812	0.58	1.3							170	7.59	23		2932	0.56	0.8					
27.9	171	6.75	23.2	6.23	1752		1.4	344.2	390.6	0.87	1.17	0.549		171	7.50	23.6	5.09	2851		0.8	356.6	401.8	0.94	6.92	0.099
28.9	172	7.23	23.9	4.98	1896	0.55	1.3							172	7.01	24	4.80	3090	0.59	0.8					
29.9	173	7.63	23.7	5.29	1532		1.5	360.6	362.6	0.89	9.46	0.066		173	6.94	23.7	4.80	2950		0.8	332	424.2	0.96	1.81	0.380
30.9	174				1592		1.5							174				3079		0.8					
1.10	175				1592	0.45	1.5							175				3079	0.58	0.8					
2.10	176	8.56	21.2	7.87	1660		1.5	437.6	288.4	0.89	71.99	0.007		176	6.87	20.5	6.90	2779		0.9	334.2	421.4	0.93	1.23	0.483
3.10	177	8.39	22.8	6.79	1756	0.36	1.4							177	7.04	22.8	6.01	2920	0.58	0.8					
4.10	178	8.41	22.9	7.00	1206		2.2	519.8	224	0.92	70.41	0.007		178	7.09	23.1	5.54	3281		0.8	346	441	0.99	2.55	0.284
5.10	179	7.96	23.2	6.46	1245	0.46	2.1							179	7.12	23.3	5.03	3478	0.60	0.7					
6.10	180	8.22	23.5	6.65	714		3.4	470.6	282.8	0.94	44.61	0.013		180	7.12	23.7	5.10	1947		1.3	345	428.4	0.98	2.84	0.254
7.10	181				586		4.2							181				1571		1.6					
8.10	182				586	0.52	4.2							182				1571	0.59	1.6					
9.10	183	6.05	22.4	8.21	990		2.4	389.6	364	0.94	0.25	2.616		183	6.01	21.3	8.38	2797		0.8	332.4	417.2	0.94	0.18	3.383
10.10	184	8.00	23	7.20	1086	0.41	2.2							184	7.30	22.5	6.11	3069	0.56	0.8					
11.10	185	7.90	23.3	6.73	1298		1.9	470.6	282.8	0.94	21.95	0.028		185	7.13	23.1	5.68	3711		0.6	345	428.4	0.98	2.78	0.252
12.10	186	7.81	23.8	6.15	1300	0.56	1.8							186	6.26	23.8	7.59	3717	0.55	0.6					
13.10	187	6.98	24.2	6.48	595		4.1	356.2	392	0.93	2.20	0.316		187	7.67	23.9	5.06	1445		1.7	359.6	382.2	0.93	10.47	0.063
14.10	188				268		9.2							188				382		6.4					
15.10	189				268	0.58	9.2							189				382	0.59	6.4					

R1	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
16.10	190	6.02	23.2	8.18	918		2.6	345.6	371	0.88	0.22	2.797		190	6.06	24.5	8.19	1582		1.5	334.4	403.2	0.93	0.26	2.680
17.10	191	7.13	23.7	6.62	1021	0.55	2.3							191	6.71	23.9	5.98	1768	0.56	1.3					
18.10	192	7.15	23.9	6.35	1007		2.3	356.2	407.4	0.95	3.18	0.224		192	6.00	23.9	7.54	2230		1.1	348.2	436.8	0.95	0.22	3.385
19.10	193	7.22	23.6	6.87	1069	0.53	2.2							193	6.81	23.7	5.39	2557	0.56	0.9					
20.10	194	7.48	23.1	7.07	1014		2.4	365.8	383.6	0.91	6.55	0.101		194	6.56	23.4	6.21	2475		1.0	343.8	418.6	0.94	0.77	0.907
21.10	195				1066		2.3							195				2606		1.0					
22.10	196				1066	0.53	2.3							196				2606	0.57	1.0					
23.10	197	7.93	22.3	7.30	1026		2.3	389.8	371	0.99	18.12	0.035		197	6.62	22.5	6.69	2449		1.0	357	429.8	0.99	0.86	0.830
24.10	198	7.74	22.6	7.24	1059	0.51	2.2							198	6.69	22.7	5.96	2528	0.56	0.9					
25.10	199	7.86	22.7	6.80	944		2.5	387.2	386.4	0.96	15.85	0.043		199	6.61	22.9	5.82	1960		1.2	348	434	0.98	0.84	0.849
26.10	200				983		2.4							200				2035		1.2					
27.10	201				1032		2.4							201				2137		1.2					
28.10	202				1032		2.4							202				2137		1.2					
29.10	203				1032		2.4							203				2137		1.2					
30.10	204	6.62	21.7		943	0.57	2.5							204	6.92	21.4		2199	0.56	1.1					
31.10	205	7.00	22.1	7.66	931		2.6	346.4	407.4	0.93	1.93	0.332		205	6.66	22.2	6.86	2398		1.0	353.6	434	0.94	0.91	0.771
1.11	206				971		2.5							206				2514		1.0					
2.11	207				971	0.55	2.5							207				2514	0.58	1.0					
3.11	208	7.18	22.4	7.46	991		2.4	359	411.6	0.94	3.09	0.220		208	5.86	22.3	8.86	0		####	334.6	417.2	0.97	0.14	4.650
4.11	209				1034		2.3							209				0		####					
5.11	210				1034	0.55	2.3							210				0	0.58	####					
6.11	211	7.24	21.6	6.71	940		2.5	360.2	404.6	0.93	3.35	0.192		211	6.04	21.2	8.95	2377		1.0	335.6	424.2	0.98	0.19	3.220
7.11	212	7.16			979		2.4							212	6.90	22.2	5.32	2564	0.51	0.9					
8.11	213	7.36	23	6.50	979		2.4							213	7.75	23.2	4.10	2564		0.9	392.4	407.4	0.96	13.01	0.057
9.11	214	6.89	22.7	8.16	979	0.58	2.4							214	6.57	23.1	6.68	2564	0.62	0.9					
10.11	215	5.96	22.4	9.01	1083		2.4	333	385	0.90	0.17	3.402		215	6.62	22.7	6.41	2608		1.0	303	380.8	0.96	0.74	0.732
11.11	216				1145		2.3							216				2696		1.0					

R1	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]
12.11	217				1145		2.3							217				2696		1.0					
13.11	218	7.41	22.2	7.37	1145	0.57	2.3							218	7.07	22.4	6.01	2696	0.59	1.0					
14.11	219	7.06	22.2	7.28	1040		2.6	373.2	406	0.91	2.40	0.287		219	6.71	22.1	5.73	2215		1.2	360.8	424.2	0.95	1.03	0.673
15.11	220	6.95	22.7	7.88	1083		2.5							220	6.73	23	6.11	2243		1.2					
16.11	221	7.02	22.5	7.44	654	0.57	4.1							221	6.58	22.7	6.09	2243	0.59	1.2					
17.11	222	7.11	21.5		1007		2.5	378.2	408.8	0.93	2.60	0.263		222	6.63	22.3	6.12	3406		0.7	366.4	442.4	1.00	0.89	0.840
18.11	223				1249		2.0							223				4852		0.5					
19.11	224				1249		2.0							224				4852		0.5					
20.11	225	7.60	21.1	8.20	1249	0.58	2.0							225	7.22	20.4	7.25	4852	0.59	0.5					
21.11	226	7.02	21.9	7.01	995		2.6	356.4	407.4	0.90	2.05	0.318		226	7.31	21.6	5.26	4603		0.6	344.2	392	0.94	3.76	0.158
22.11	227	7.03	22.2	6.98	1032		2.5							227	7.83	22.7	4.63	4980		0.5					
23.11	228	7.27	22.3	7.12	1032	0.54	2.5							228	8.10	22.8	4.85	4980	0.35	0.5					
24.11	229	7.51	22.5	7.29	1005		2.6	387	408.8	0.94	7.11	0.102		229	8.26	23	4.82	3230		0.8	552.4	253.4	0.96	55.12	0.011
25.11	230				1077		2.4							230				2942		0.9					
26.11	231				1077	0.54	2.4							231				2942	0.55	0.9					
27.11	232	7.40	21.2	7.29	1130		2.3	396.6	420	0.93	5.16	0.139		232	6.93	21.7	5.98	4558		0.6	389.2	445.2	0.95	1.79	0.430
28.11	233	6.99	21.2	7.19	1179		2.2							233	7.94	21.7	5.13	4756		0.5					
29.11	234	7.02	21.5	7.07	1179	0.55	2.2							234	7.95	21.9	5.21	4756	0.52	0.5					
30.11	235	7.07	21.5	7.11	123		21.2	388.6	414.4	0.84	2.43	0.292		235	7.79	21.9	5.20	496		5.3	419.4	397.6	0.94	13.88	0.053
1.12	236				0		####							236				0		####					
2.12	237				0		####							237				0		####					
3.12	238				0		####							238				0		####					
4.12	239				0	0.57	####							239				0	0.60	####					
5.12	240	6.01	22.2	2.80	660		4.0	376.2	408.8	0.91	0.22	3.237		240	8.37	22	0.74	1844		1.4	351	327.6	0.97	41.29	0.011
6.12	241	7.59	20.7	7.53	1092	0.54	2.4							241	7.58	21.3	6.36	3052	0.55	0.9					
7.12	242	7.85	21.1	7.85	985		2.7	401	394.8	0.90	14.33	0.047		242	7.30	21.6	5.83	3416		0.8	396	413	0.92	4.23	0.171
8.12	243				963		2.7							243			5.83	3717		0.7					

R1	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
9.12	244				963		2.7							244				3717		0.7					
10.12	245				963	0.56	2.7							245				3717	0.44	0.7					
11.12	246	7.43	18.1	8.05	726		3.7	387.2	411.6	0.87	4.30	0.139		246	8.21	19.5	5.88	2559		1.0	488.2	329	0.87	34.48	0.018
12.12	247	7.49	20.4	7.57	820		3.3							247	7.23	21.1	5.95	2890		0.9					
13.12	248	5.75	20.4	8.50	820		3.3							248	6.64	21.4	6.00	2890		0.9					
14.12	249				820	0.55	3.3							249				2890	0.58	0.9					
15.12	250	7.73	20.4	6.83	945		2.8	399.6	378	0.93	10.38	0.060		250	6.74	19.6	6.96	3400		0.8	379	421.4	0.93	0.97	0.667
16.12	251				980		2.7							251				3543		0.8					
17.12	252				980		2.7							252				3543		0.8					
18.12	253	7.06	20.4	8.09	980	0.57	2.7							253	8.14	21.1	5.58	3543	0.40	0.8					
19.12	254	7.14	20.5	8.12	980		2.8	382	410.2	0.92	2.61	0.252		254	8.07	21.3	5.50	2796		1.0	533.6	340.2	0.94	31.49	0.024
20.12	255	7.16	20.4	8.42	1023		2.7							255	7.20	20.7	6.72	2910		0.9					
21.12	256	6.73	20.4	8.39	1023	0.77	2.7							256	6.86	21	7.03	2910	0.76	0.9					
22.12	257	6.77	20.7	8.70	993		2.7							257	7.00	21.3	6.96	3139		0.8					
23.12	258				1053		2.5							258				3358		0.8					
24.12	259				1053		2.5							259				3358		0.8					
25.12	260				1053		2.5							260				3358		0.8					
26.12	261				1053		2.5							261				3358		0.8					
27.12	262				1053		2.5							262				3358		0.8					
28.12	263				1053	0.59	2.5							263				3358	0.59	0.8					
29.12	264	7.26	19.1	8.00	907		3.0	364.6	341.6	0.80	2.96	0.166		264	7.30	19.3	6.52	3025		0.9	362.8	399	0.96	3.27	0.175
30.12	265				910		2.9							265				3083		0.9					
31.12	266				910		2.9							266				3083		0.9					
1.1	267				910	0.71	2.9							267				3083	0.56	0.9					
2.1	268	5.82	19.6	8.55	936		2.9							268	7.55	19.9	6.18	3188		0.8	395.4	415.8	0.98	6.59	0.101
3.1	269				918		2.9							269				3131		0.9					
4.1	270				918		2.9							270				3131		0.9					

R1	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
5.1	271				918		2.9							271				3131		0.9					
6.1	272				918		2.9							272				3131		0.9					
7.1	273				918	0.56	2.9							273				3131	0.54	0.9					
8.1	274	7.35	19	8.82	1016		2.6	395.4	232.4	0.52	3.91	0.092		274	7.58	20.1	6.42	2923		0.9	411.4	400.4	0.95	7.45	0.090
9.1	275	6.61	21.3	6.91	1077		2.4							275	7.29	21.9	5.32	3084		0.9					
10.1	276	6.74	21	6.95	1077	0.56	2.4							276	7.07	21.5	5.17	3084	0.56	0.9					
11.1	277	6.69	20.5	6.85	1009		2.6	385.2	131.6	0.29	0.94	0.228		277	7.16	20.9	5.91	2127		1.2	389.8	446.6	0.98	2.87	0.260
12.1	278	6.93	20	7.52	1045		2.5							278	7.17	20.6	6.03	2004		1.3					
13.1	279				1045		2.5							279				2004		1.3					
14.1	280				1045		2.5							280				2004		1.3					
15.1	281	7.16	19.3	7.71	688	0.61	4.3							281	5.84	19	8.81	3361	0.55	0.9					
16.1	282	5.58	19.3	8.33	1144		2.6	376.6	30.6	0.07	0.07	0.701		282	7.66	19.6	5.84	3922		0.7	444	401.8	0.96	9.29	0.077
17.1	283	7.99	19.8	7.55	1194		2.5							283	7.84	19.8	5.54	3922		0.7					
18.1	284	8.14	19.9	7.73	992		2.7							284	7.81	20.4	5.47	2746		1.0					
19.1	285	7.92	20.9	7.41	1042		2.6							285	7.27	21.1	6.04	2836		1.0					
20.1	286				1042		2.6							286				2836		1.0					
21.1	287				1042	0.56	2.6							287				2836	0.57	1.0					
22.1	288	7.45	19.7	7.95	1113		2.7	397.6	163.8	0.39	5.20	0.050		288	6.48	20.2	7.29	3185		0.9	385.8	432.6	1.00	0.57	1.226
23.1	289	7.89	19.9	7.80	1166		2.5							289	7.35	20	6.72	3369		0.9					
24.1	290	8.05	20.2	7.50	1166	0.53	2.5							290	7.44	20.3	6.02	3369	0.60	0.9					
25.1	291	7.97	20.1	7.48	906		3.4	461.6	229.6	0.53	20.08	0.021		291	6.94	20	6.78	2783		1.1	398.2	434	0.96	1.66	0.429
26.1	292				915		3.3							292				2836		1.1					
27.1	293				915		3.3							293				2836		1.1					
28.1	294				915	0.59	3.3							294				2836	0.55	1.1					
29.1	295	5.85	19.1	8.92	1083		2.8	412.4	319.2	0.68	0.13	3.963		295	6.81	18.6	7.29	3152		1.0	451.8	463.4	0.95	1.26	0.642
30.1	296				1150		2.7							296				3331		0.9					
31.1	297	7.39	20.7	7.50	1150		2.7							297	7.10	20.9		3331		0.9					

R1	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]	R2	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]
1.2	298	7.61	20.9	7.52	1150	0.52	2.7							298	7.13	20.7	6.49	3331	0.54	0.9					
2.2	299	7.30	20.3	7.57	1150		2.8	489.4	308	0.65	4.75	0.132		299	7.33	20.6	6.19	3237		1.0	464	434	0.94	4.93	0.172
3.2	300				1200		2.7							300				3377		1.0					
4.2	301				1200	0.54	2.7							301				3377	0.56	1.0					
5.2	302	8.13	19.2	8.03	1166		2.7	495	313.6	0.68	28.75	0.020		302	6.98	19.9	6.36	3283		1.0	468.6	456.4	0.94	2.12	0.413
6.2	303	7.94	19.5	7.51	1093		2.9							303	7.32	20	6.57	4448		0.7					
7.2	304	7.18	19.9	7.51	1141		2.7							304	8.26	20.4	6.13	4642		0.7					
8.2	305	7.14	20.3	7.71	1060	0.53	2.7							305	8.18	20.9	5.85	4316	0.41	0.7					
9.2	306	7.39	19.7	7.99	1020		2.8	452.6	261.8	0.53	5.16	0.093		306	8.31	20.5	5.74	3862		0.8	571.6	303.8	0.92	53.61	0.013
10.2	307				1066		2.7							307				3929		0.7					
11.2	308				1066		2.7							308				3929		0.7					
12.2	309	7.86	18.8	8.05	1066	0.54	2.7							309	8.35	19.8	5.02	3929	0.33	0.7					
13.2	310	6.84	20.1	7.68	1320		2.3	447.2	156.8	0.31	1.49	0.195		310	8.41	20.8	4.50	2906		1.0	649.8	259	0.92	76.73	0.008
14.2	311	8.22	20.8	7.94	1474		2.0							311	8.35	21.4	4.60	3167		0.9					
15.2	312	8.35	21	7.58	1474	0.48	2.0							312	8.16	21.6	4.92	3167	0.46	0.9					
16.2	313	8.29	20.6	7.55	1345		2.2	513.4	193.2	0.46	46.46	0.008		313	8.06	21.2	5.01	2879		1.0	534.4	347.2	0.93	30.64	0.025
17.2	314	8.36	20.6	7.62	1400		2.1							314	8.01	20.8	4.79	2994		1.0					
18.2	315				1400		2.1							315				2994		1.0					
19.2	316	8.31	20.4	7.69	1400	0.51	2.1							316	7.91	20.7	4.96	2994	0.52	1.0					
20.2	317	8.09	20.6	7.24	1229		2.3	481.2	326.2	0.75	28.25	0.022		317	7.67	20.9	4.89	2949		1.0	468.8	456.4	0.99	11.02	0.082
21.2	318	7.76	20.5	7.23	1265		2.2							318	7.36	20.6	5.54	3051		0.9					
22.2	319	7.90	21.2	7.22	1265	0.52	2.2							319	6.87	21.3	6.14	3051	0.48	0.9					
23.2	320	7.76	20.4	7.64	1307		2.3	458.6	340.2	0.74	12.74	0.050		320	7.79	20.8	5.51	3016		1.0	487.2	434	0.95	14.90	0.059
24.2	321				201		15.0							321				3016		1.0					
25.2	322				0		####							322				3016		1.0					
26.2	323				0		####							323				2011		1.5					
27.2	324				0	0.57	####							324				1005	0.54	3.0					
28.2	325	6.02	19.2	8.66	935		3.0	431.4		0.69	0.20	2.828		325	6.78	19.5	6.51	3237		0.9	460.6	501.2	0.97	1.28	0.726

Table 18: Performance data R3 and R4

R3	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
9.6	1	6.30			123	1.00	23.1							1	6.30			123		23.1					
10.6	2													2				0		0.0					
11.6	3					0.60								3				0	0.61	0.0					
12.6	4	6.05			201		14.2	376.0	456.0	0.96				4	6.05			201		14.2	371.2	439.0	0.92		
13.6	5	6.06			95	0.61	30.0							5	6.05			95	0.61	30.0					
14.6	6				121		23.6	370.5	456.0	0.99				6	6.04			121		23.6	372.4	452.0	0.97		
15.6	7					0.58								7				0	0.67	0.0					
16.6	8	6.02			161		17.6	401.1	505.0	0.96				8	6.04			161		17.6	313.1	401.0	0.91		
17.6	9													9				0		0.0					
18.6	10					0.62								10				0	0.62	0.0					
19.6	11	6.04			201		14.2	362.0	459.0	0.95				11	6.04			201		14.2	359.6	465.0	0.96		
20.6	12	6.02			236	0.62	12.5							12	6.01			236	0.62	12.5					
21.6	13	6.00			260		11.1	371.7	482.0	1.00				13	6.04			260		11.1	372.0	489.0	1.02		
22.6	14	6.02			289	0.66	10.0							14	6.02			289	0.67	10.0					
23.6	15	5.98			362		8.6	325.5	380.0	0.89				15	5.99			362		8.6	321.1	370.0	0.86		
24.6	16				0									16				0		0.0					
25.6	17				0	0.62								17				0	0.63	0.0					
26.6	18	6.08			383		8.1	396.5	446.0	0.89				18	6.07			383		8.1	386.5	452.0	0.90		
27.6	19	6.01			415	0.63	7.5							19	6.15			415	0.62	7.5					
28.6	20	6.12	25.1		398		7.5	382.8	475.0	0.99	0.35	2.71		20	7.13	26.0		398		7.5	397.5	479.0	0.97	3.94	0.26
29.6	21	6.01	25.8	7.59	591	0.59	5.0	394.0	483.0	0.99				21	6.01	25.8	7.70	431	0.59	6.9	401.8	488.5	0.98		
30.6	22	7.22			591		5.0	405.1	491.0	0.99				22	7.08			508		5.8	406.0	498.0	1.00	0.48	0.63
1.7	23				614		4.8							23				539		5.5					
2.7	24				614	0.56	4.8							24				539	0.57	5.5					
3.7	25	6.75	23.4	8.24	660		4.5	435.1	505.0	0.89	1.50	0.71		25	6.75	23.6	8.17	703		4.2	423.6	502.8	0.92	1.48	0.70
4.7	26	7.10	24.6	7.01	692	0.56	4.2							26	7.17	24.9	7.03	737	0.57	3.9					
5.7	27	7.10			684		4.0	424.8	523.2	0.97				27	7.06		0.00	583		4.7	418.8	513.6	0.96	0.00	0.00

R3	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
6.7	28	7.18			722	0.68	3.8							28	6.81			615	0.62	4.4					
7.7	29	5.80			798		3.5	290.2	352.8	0.93				29	6.81			630		4.4	348.4	431.2	0.92	0.22	1.02
8.7	30				860		3.3							30				671		4.2					
9.7	31				860	0.55	3.3							31				671	0.55	4.2					
10.7	32	6.79	25.3	6.72	793		3.6	418.4	522.2	0.96	1.81	0.63		32	6.78	25.1	6.82	655		4.4	422.0	519.4	0.93	1.76	0.65
11.7	33	7.27	25.2		922	0.57	3.2							33	7.03	25.3		773	0.57	3.8					
12.7	34	7.07	25.7	7.08	1140		2.5	422.2	512.0	0.96	3.57	0.32		34	7.10	25.3	7.38	1000		2.9	421.6	502.4	0.95	3.71	0.30
13.7	35	7.67	25.3		1219	0.58	2.4							35	7.37	25.1		1069	0.56	2.7					
14.7	36	7.53	24.4		1175		2.5	407.2	502.0	0.93	8.95	0.11		36	7.20	23.8		976		3.0	424.4	480.0	0.89	4.22	0.24
15.7	37				1244		2.3							37				1019		2.9					
16.7	38				1244	0.51	2.3							38				1019	0.50	2.9					
17.7	39	7.89	22.9		52	0.57	56.0	470.4	499.2	0.96	20.87	0.05		39	7.96	22.3		42	0.57	68.4	483.6	481.6	0.91	24.02	0.04
18.7	40	5.92	23.8	7.93	855	0.58	3.4	415.6	502.4	0.93	0.22	4.69		40	5.89	23.3	6.72	792	0.59	3.7	420.4	488.0	0.92	0.20	4.95
19.7	41	7.14	24.7	7.03	966		2.8	409.4	496.0	0.97	3.79	0.27		41	7.02	24.5		937		2.9	400.8	476.8	0.92	2.78	0.35
20.7	42	7.68	23.5		1008	0.53	2.7							42	7.50	23.3		979	0.51	2.8					
21.7	43	8.18	23.9	6.87	412		6.9	432.0	424.0	0.89	38.62	0.02		43	8.24	23.7	6.74	405		7.0	446.2	412.8	0.87	44.71	0.02
22.7	44				536		5.3							44				527		5.4					
23.7	45				536	0.60	5.3							45				527	0.57	5.4					
24.7	46	7.25	25.2	6.50	594		4.3	367.6	396.8	0.77	4.53	0.17		46	8.30	25.2	6.13	438		5.9	408.8	380.8	0.88	51.20	0.01
25.7	47	6.90	24.7		681	0.57	3.8							47	6.94	24.7		730	0.55	3.5					
26.7	48	7.41	24.7		664		4.1	378.4	259.2	0.54	6.48	0.08		48	8.06	24.7		610		4.4	384.6	361.6	0.86	28.03	0.02
27.7	49	6.72	24.5		766	0.58	3.5							49	6.98	24.4		797	0.61	3.4					
28.7	50	6.61	24.0		1023		2.7	369.4	144.0	0.29	0.96	0.27		50	6.94	24.0		993		2.7	355.2	360.0	0.77	1.98	0.32
29.7	51				1114		2.4							51				1073		2.5					
30.7	52				1114	0.60	2.4							52				1114	0.58	2.4					
31.7	53	7.32	24.8	5.56	1010		2.7	356.2	243.2	0.54	5.00	0.09		53	7.70	24.8		1057		2.6	382.4	358.4	0.81	12.68	0.05
1.8	54	7.09	24.6	6.79	1127	0.60	2.4							54	7.24	24.6		1184	0.60	2.3					

R3	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
2.8	55	7.11	25.8	5.91	1299	0.59	2.1	369.8	204.8	0.43	3.45	0.12		55	7.32	25.8		1317	0.55	2.1	366.0	358.4	0.78	5.52	0.13
3.8	56	7.81	24.4	5.08	1267	0.56	2.2	402.8	243.2	0.51	16.61	0.03		56	7.84	24.3		1192	0.50	2.3	414.0	361.6	0.81	18.12	0.04
4.8	57	8.06	24.2	5.38	1508		1.8	446.2	254.4	0.58	31.44	0.02		57	7.85	24.5		1179		2.3	450.8	355.2	0.82	20.45	0.04
5.8	58				1557		1.8							58				1217		2.3					
6.8	59				1557		1.8							59				1217		2.3					
7.8	60	7.86	24.2	5.63	1442	0.43	1.9							60	8.13	23.9		1171	0.44	2.4					
8.8	61	8.48	23.9	6.72	684	0.40	4.1	555.6	212.8	0.77	92.34	0.01		61	8.42	23.8		683	0.49	4.1	510.8	264.0	0.85	74.79	0.01
9.8	62	8.13	24.5	5.96	659		4.2	488.0	297.6	0.79	40.80	0.02		62	8.30	24.3		643		4.3	477.6	304.0	0.84	56.45	0.01
10.8	63	6.87	24.2	6.98	1169	0.49	2.4							63	7.86	24.1		635	0.57	4.4					
11.8	64	7.75	24.6	5.98	1500		1.8	454.6	342.4	0.74	16.62	0.05		64	7.59	24.2	6.72	562		4.7	399.6	379.2	0.86	9.92	0.08
12.8	65				1640		1.6							65				613		4.3					
13.8	66				1640	0.54	1.6							66				613	0.57	4.3					
14.8	67	7.47	24.4	6.71	1255		2.2	394.8	360.0	0.75	7.58	0.09		67	7.52	24.3	7.17	589		4.6	382.4	339.2	0.75	8.16	0.08
15.8	68				1281	0.54	2.1							68				601	0.61	4.5					
16.8	69	7.89	24.5	6.58	1138		2.3	430.8	371.2	0.80	21.35	0.04		69	7.20	24.3	7.14	675		4.0	347.8	292.8	0.66	3.59	0.14
17.8	70	8.03	24.2	6.90	1168	0.51	2.3							70	7.48	24.1	6.84	716	0.61	3.7					
18.8	71	8.14	24.5	6.55	1010		2.6	432.2	339.2	0.80	36.92	0.02		71	7.20	24.3	6.76	1023		2.5	348.2	302.4	0.68	0.00	0.00
19.8	72				1032		2.5							72				1044		2.5					
20.8	73				1032	0.45	2.5							73				1044	0.51	2.5					
21.8	74	8.45	24.3	6.92	871		3.0	495.0	323.2	0.81	79.45	0.01		74	7.89	24.4	6.14	635		4.1	422.2	360.0	0.76	20.78	0.04
22.8	75				921	0.41	2.8							75				646	0.55	4.0					
23.8	76	8.50	24.1	6.60	967		2.6	528.8	310.4	0.88	92.57	0.01		76	6.34	24.1	7.80	920		2.7	389.6	427.2	0.85	0.55	1.51
24.8	77	8.17	24.1	6.15	1040	0.39	2.4							77	7.71	24.1	5.83	939	0.49	2.7					
25.8	78	8.14	24.1	6.41	908		2.8	493.2	366.4	0.91	41.02	0.02		78	7.81	24.1	5.97	886		2.8	423.8	406.4	0.88	17.11	0.05
26.8	79				973		2.6							79				955		2.6					
27.8	80				973	0.48	2.6							80				955	0.51	2.6					
28.8	81	7.29	24.4	6.48	1173		2.2	414.8	425.6	0.91	5.29	0.17		81	7.54	24.4	5.91	1081		2.4	405.2	424.0	0.93	9.11	0.09

	R3 pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4 pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
29.8	82	8.11	24.1	5.99	1247	0.50	2.1						82	7.98	24.1	5.76	1146	0.48	2.3					
30.8	83	8.28	24.4	6.24	940		2.6	465.0	369.6	0.98	53.06	0.01	83	8.11	24.4	6.14	648		3.8	459.6	398.4	0.98	36.57	0.02
31.8	84	7.45	24.0	5.95	981	0.50	2.5						84	7.58	24.0	5.52	676	0.62	3.6					
1.9	85	7.12	24.2	6.40	839		3.1	357.8	375.6	0.86	3.05	0.22	85	6.06	24.1	7.84	830		3.1	312.4	333.6	0.81	0.23	2.24
2.9	86				815		3.2						86				897		2.9					
3.9	87				815	0.56	3.2						87				897	0.55	2.9					
4.9	88	7.40	24.4	6.11	1202		2.1	394.4	405.6	0.86	6.46	0.12	88	7.12	24.5	5.97	1155		2.2	386.8	429.6	0.90	3.37	0.25
5.9	89	7.53	24.4	5.71	1286	0.54	2.0						89	7.76	24.5	5.52	1228	0.47	2.1					
6.9	90	7.51	24.2	5.96	1279		2.1	402.2	396.0	0.90	8.33	0.09	90	7.93	24.4	5.64	1259		2.1	459.4	367.2	0.94	24.70	0.03
7.9	91	7.55	24.3	6.09	1335	0.53	2.0						91	7.94	24.5	5.75	1315	0.43	2.0					
8.9	92	7.58	24.2	6.28	1130		2.2	421.4	402.0	0.90	10.23	0.08	92	8.06	24.5	5.71	1091		2.3	500.4	330.0	0.89	35.98	0.02
9.9	93				1215		2.1						93				1172		2.2					
10.9	94				1215	0.50	2.1						94				1172	0.41	2.2					
11.9	95	7.83	24.0	6.54	1222		2.1	421.8	392.4	0.92	17.68	0.04	95	8.14	24.3	6.13	1178		2.2	498.2	339.6	0.94	41.99	0.02
12.9	96	7.69	24.0	6.32	1233	0.51	2.1						96	8.12	24.3	7.35	1235	0.45	2.1					
13.9	97	7.66	23.6	6.73	1181		2.2	409.0	402.0	0.90	11.40	0.07	97	8.09	23.9	6.17	1132		2.3	466.0	314.4	0.90	34.34	0.02
14.9	98	7.47	23.1	6.00	1245	0.53	2.1						98	7.10	23.3	4.16	1194	0.58	2.2					
15.9	99	7.46	23.0	6.35	1069		2.2	398.4	421.4	0.93	6.77	0.12	99	6.81	23.1	5.67	1038		2.3	360.2	421.4	0.95	1.40	0.52
16.9	100				1112		2.1						100				1083		2.2					
17.9	101				1112	0.47	2.1						101				1083	0.36	2.2					
18.9	102	8.03	22.4	6.59	1063		2.3	421.6	361.2	0.94	24.60	0.03	102	8.43	22.6	7.79	529		4.6	503.0	257.6	0.92	69.62	0.01
19.9	103	7.95	22.7	6.15	1147	0.52	2.1						103	8.46	22.8	7.15	551	0.43	4.4					
20.9	104	7.37	22.7	6.02	1085		2.2	358.8	417.2	0.95	4.86	0.14	104	8.12	22.6	5.88	682		3.5	461.2	273.0	0.92	33.20	0.02
21.9	105	7.18	22.7	5.92	1147		2.1						105	7.23	22.7	5.60	745		3.2					
22.9	106	7.40	22.5		963		2.5						106	6.35	22.5		962		2.5					
23.9	107				936		2.6						107				1050		2.3					
24.9	108				936	0.52	2.6						108				1050	0.37	2.3					

R3 [d]	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4 [d]	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
25.9	109	7.62	22.8	7.03	1106		2.2	384.4	410.2	0.91	9.25	0.08		109	8.35	23.0	6.90	710		3.4	504.6	270.2	0.97	60.80	0.01
26.9	110	8.28	22.8		1162	0.49	2.1							110	8.44	22.7		659	0.32	3.7					
27.9	111	8.18	23.0	6.28	928		2.6	442.0	309.4	0.88	37.20	0.02		111	8.58	23.0	6.90	795		3.0	558.2	172.2	0.91	106.82	0.00
28.9	112	7.48	22.8	6.19	944	0.50	2.5							112	8.22	22.8	5.53	909	0.42	2.6					
29.9	113	7.27	22.9	6.80	912		2.6	353.6	393.4	0.91	3.87	0.17		113	7.81	22.9	5.84	862		2.8	461.8	273.0	0.93	17.15	0.03
30.9	114				952		2.5							114				899		2.6					
1.10	115				952	0.56	2.5							115				899	0.40	2.6					
2.10	116	7.27	22.8	6.92	938		2.6	345.8	392.0	0.90	3.76	0.17		116	8.30	22.9	6.49	853		2.9	477.0	253.4	0.92	51.44	0.01
3.10	117	7.90	22.7	6.81	990	0.56	2.5							117	8.14	22.8	6.25	899	0.38	2.7					
4.10	118	7.97	22.9	6.68	768		3.4	374.4	373.8	0.93	19.82	0.03		118	8.22	22.9	6.60	779		3.3	506.4	256.2	0.97	46.11	0.01
5.10	119	7.50	23.2	6.56	800	0.58	3.2							119	8.31	23.3	6.63	816	0.38	3.2					
6.10	120	7.40	23.1	6.80	213		11.5	357.0	408.8	0.95	5.33	0.13		120	8.33	23.2	6.65	503		4.9	540.2	214.2	0.97	63.26	0.01
7.10	121				34		71.2							121				432		5.6					
8.10	122				34	0.58	71.2							122				432	0.46	5.6					
9.10	123	6.15	23.0	8.15	629		3.8	340.8	411.6	0.88	0.29	2.31		123	6.02	23.2	8.08	671		3.5	440.8	319.2	0.93	0.28	2.41
10.10	124	8.16	23.2	7.16	694	0.56	3.4							124	7.71	23.3	5.98	735	0.32	3.2					
11.10	125	8.00	23.3	6.84	628		3.8	357.0	408.8	0.95	20.75	0.03		125	7.70	23.3	5.87	819		2.9	540.2	214.2	0.97	16.13	0.03
12.10	126	6.24	22.8	8.07	627	0.54	3.8							126	7.64	23.0	6.00	820	0.50	2.9					
13.10	127	7.77	22.9	6.85	265		9.3	372.6	362.6	0.88	12.65	0.05		127	7.72	23.0	6.14	405		6.1	402.8	341.6	0.89	12.31	0.05
14.10	128				97		25.5							128				214		11.5					
15.10	129				97	0.57	25.5							129				214	0.55	11.5					
16.10	130	6.12	22.8	8.23	615		3.9	350.8	386.4	0.90	0.27	2.34		130	6.02	22.8	8.23	559		4.3	365.8	386.4	0.93	0.23	2.94
17.10	131	7.78	22.9	6.79	693	0.54	3.4							131	7.74	22.9	6.44	290	0.54	8.2					
18.10	132	7.73	23.0	6.80	698		3.4	379.8	390.6	0.91	11.87	0.06		132	6.82	23.0	6.40	539		4.4	369.8	411.6	0.94	1.46	0.50
19.10	133	7.58	21.1	6.81	746	0.53	3.2							133	7.11	21.1	6.30	544	0.55	4.3					
20.10	134	7.53	21.1	7.82	506		4.9	360.6	389.2	0.92	6.27	0.10		134	5.80	21.0	9.04	262		9.5	355.2	413.0	0.94	0.12	5.47
21.10	135				519		4.8							135				259		9.6					

R3 [d]	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4 [d]	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
22.10	136				519	0.61	4.8							136				259	0.57	9.6					
23.10	137	5.96	21.2	9.00	729		3.2	311.4	379.4	0.96	0.15	3.46		137	7.13	21.1	7.66	679		3.5	358.0	407.4	0.97	2.50	0.25
24.10	138	7.60	21.2	7.46	753	0.57	3.1							138	7.21	21.1	6.66	701	0.54	3.4					
25.10	139	7.67	21.1	7.48	672		3.5	366.8	399.0	0.95	8.75	0.07		139	7.41	21.0	6.36	656		3.6	364.2	393.4	0.94	4.78	0.13
26.10	140				700		3.4							140				684		3.5					
27.10	141				735		3.4							141				719		3.5					
28.10	142				735		3.4							142				719		3.5					
29.10	143				735		3.4							143				719		3.5					
30.10	144	8.08	21.1		650	0.50	3.7							144	7.30	21.1		607	0.55	3.9					
31.10	145	8.04	21.1	6.86	691		3.5	399.0	355.6	0.91	21.74	0.03		145	7.34	21.0	7.39	657		3.7	359.8	411.6	0.89	4.03	0.16
1.11	146				724		3.3							146				690		3.5					
2.11	147				724	0.41	3.3							147				690	0.53	3.5					
3.11	148	8.35	21.4	6.69	648		3.7	495.8	295.4	0.91	53.76	0.01		148	7.61	21.4	6.56	613		4.0	377.2	407.4	0.96	8.03	0.08
4.11	149				676		3.6							149				639		3.8					
5.11	150				676	0.37	3.6							150				639	0.52	3.8					
6.11	151	8.28	21.2	6.33	694		3.5	511.0	278.6	0.94	47.15	0.01		151	7.57	21.2	6.56	652		3.7	384.2	411.6	0.93	7.36	0.09
7.11	152	8.07	21.0	6.38	726		3.3							152	8.11	20.9	6.84	682		3.5					
8.11	153	7.79	22.0	5.62	726		3.3							153	7.80	22.0	5.53	682		3.5					
9.11	154	7.25	21.5	8.39	726	0.49	3.3							154	7.37	21.5	8.32	682	0.54	3.5					
10.11	155	7.20	21.5	8.50	730		3.6	368.6	392.0	0.95	3.11	0.20		155	7.22	21.6	8.80	677		3.9	368.6	392.0	0.95	3.28	0.19
11.11	156				752		3.5							156				695		3.8					
12.11	157				752		3.5							157				695		3.8					
13.11	158	7.26	21.6	8.58	752	0.56	3.5							158	7.33	21.8	8.61	695	0.58	3.8					
14.11	159	7.93	21.4	8.43	690		3.8	394.0	396.2	0.93	17.19	0.04		159	7.64	21.5	8.56	696		3.8	372.2	407.4	0.91	8.54	0.08
15.11	160	7.97	21.4	8.77	721		3.7							160	7.88	21.4	8.60	743		3.6					
16.11	161	8.03	19.5	8.91	721	0.55	3.7							161	8.03	19.5	8.92	743	0.55	3.6					
17.11	162	8.12	19.3	8.93	665		3.8	404.2	392.0	0.97	23.13	0.03		162	8.18	19.3	9.12	520		4.8	401.4	378.0	0.95	26.19	0.02

R3	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	NH4 removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
18.11	163				823		3.1							163				564		4.5					
19.11	164				823		3.1							164				564		4.5					
20.11	165	8.17	19.3	8.09	823	0.49	3.1							165	8.23	19.2	8.97	564	0.51	4.5					
21.11	166	7.73	19.2	6.94	626		4.1	431.4	340.2	0.92	10.27	0.06		166	5.70		8.60	536		4.7	412.4	354.2	0.88	0.02	10.72
22.11	167	7.63	17.5	6.98	641		4.0							167	8.24	17.3	8.78	580		4.4					
23.11	168	7.69	20.3	6.54	641	0.47	4.0							168	7.91	20.0	8.20	580	0.44	4.4					
24.11	169	8.25	21.2	7.38	514		5.1	458.4	366.8	0.98	39.67	0.02		169	8.17	21.0	7.90	473		5.5	477.6	337.4	0.98	34.32	0.02
25.11	170				515		5.1							170				477		5.5					
26.11	171				515	0.50	5.1							171				477	0.40	5.5					
27.11	172	7.36	19.1	8.20	370		7.0	428.2	375.2	0.92	4.37	0.14		172	8.68	19.0	8.69	522		5.0	524.4	243.6	0.88	95.11	0.00
28.11	173	7.12	19.4	8.12	386		6.7							173	8.53	19.4	8.39	544		4.8					
29.11	174	5.95	19.5	8.43	386	0.52	6.7							174	7.93	19.4	8.44	544	0.36	4.8					
30.11	175	7.45	19.4	8.13	443		5.9	410.6	399.0	0.91	5.25	0.12		175	8.41	19.2	8.38	449		5.8	556.4	205.8	0.87	59.02	0.01
1.12	176				502		5.2							176				488		5.3					
2.12	177				502		5.2							177				488		5.3					
3.12	178				502		5.2							178				488		5.3					
4.12	179				502	0.56	5.2							179				488	0.48	5.3					
5.12	180	7.37	20.1	8.42	497		5.3	381.2	364.0	0.87	4.28	0.13		180	6.92	20.1	8.45	481		5.4	449.8	285.6	0.94	1.80	0.29
6.12	181	7.53	19.1	8.01	509	0.56	5.1							181	7.02	19.0	8.36	491	0.51	5.3					
7.12	182	7.49	19.3	7.93	551		4.7	385.0	317.8	0.67	5.36	0.09		182	6.93	19.0	8.55	562		4.6	428.6	337.4	0.90	1.62	0.35
8.12	183				591		4.4							183			8.37	617		4.2					
9.12	184				591		4.4							184				617		4.2					
10.12	185				591	0.55	4.4							185				617	0.52	4.2					
11.12	186	7.81	19.2	7.80	501		5.3	388.8	263.2	0.59	11.08	0.04		186	7.58	19.2	8.34	594		4.5	414.4	385.0	0.92	7.02	0.09
12.12	187	8.08	14.7	8.64	566		4.7							187	7.73	14.6	8.82	671		4.0					
13.12	188	5.89	15.3	9.20	566		4.7							188	7.54	15.1	8.94	671		4.0					
14.12	189				566	0.55	4.7							189				671	0.55	4.0					

R3	pd	pH	temp.	DO	load NH4	NH4 removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA	R4	pd	pH	temp.	DO	load NH4	NH4 removal	HRT	NH4 conc.	NO2 conc.	NAR	FA	FNA
[d]	[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]	[d]	[d]	[ ]	[°C]	[mgN/L]	[mgN/d]	[%]	[d]	[mgN/L]	[mgN/L]	[ ]	[mgN/L]	[mgN/L]
15.12	190	7.82	15.1	8.19	629		4.3	402.2	182.0	0.44	8.66	0.03		190	7.86	15.0	8.73	668		4.0	404.4	387.8	0.92	9.47	0.05
16.12	191				646		4.1							191				667		4.0					
17.12	192				646		4.1							192				667		4.0					
18.12	193	8.39	16.1	8.88	646	0.47	4.1							193	8.28	16.2	9.16	667	0.44	4.0					
19.12	194	8.25	16.0	7.73	349		7.8	490.8	169.4	0.45	29.49	0.01		194	8.23	15.9	7.70	285		9.5	500.8	365.4	0.93	28.60	0.02
20.12	195	7.77	19.2	8.39	361		7.5							195	6.18	19.0	9.59	294		9.3					
21.12	196	6.16	15.6	10.15	361	0.53	7.5							196	6.14	15.4	10.27	294	0.63	9.3					
22.12	197	7.41	15.9	9.04	372		7.1	408.8	155.4	0.40	3.68	0.06		197	7.18	15.7	9.84	441		6.0	335.0	294.0	0.93	1.75	0.19
23.12	198				397		6.7							198				483		5.5					
24.12	199				397		6.7							199				483		5.5					
25.12	200				397		6.7							200				483		5.5					
26.12	201				397		6.7							201				483		5.5					
27.12	202				397		6.7							202				483		5.5					
28.12	203				397	0.64	6.7							203				483	0.56	5.5					
29.12	204	5.83	14.9	9.21	446		6.0	315.2	48.2	0.14	0.07	0.70		204	7.34	15.1	8.98	451		5.9	390.0	396.2	0.95	2.82	0.18
30.12	205				486		5.5							205				465		5.8					
31.12	206				486		5.5							206				465		5.8					
1.1	207				486	0.56	5.5							207				465	0.53	5.8					
2.1	208	7.88	14.9	8.58	260		10.3	414.4	149.8	0.35	10.07	0.02		208	7.93	14.9	8.98	400		6.7	421.8	410.2	0.93	11.47	0.05
3.1	209				184		14.7							209				369		7.3					
4.1	210				184		14.7							210				369		7.3					
5.1	211				184		14.7							211				369		7.3					
6.1	212				184		14.7							212				369		7.3					
7.1	213				184	0.56	14.7							213				369	0.53	7.3					
8.1	214	5.88	14.6	10.36	479		5.5	388.0	170.8	0.36	0.09	2.24		214	7.86	15.0	10.01	473		5.6	421.8	371.0	0.83	9.87	0.05
9.1	215	7.43	15.1	8.48	517		5.1							215	7.82	14.9	8.90	504		5.2					
10.1	216	7.55	15.0	8.41	517	0.53	5.1							216	7.95	14.7	8.81	504	0.52	5.2					

R3	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]	R4	pd [d]	pH []	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR []	FA [mgN/L]	FNA [mgN/L]
11.1	217	7.80	14.8	8.60	473		5.6	416.6	127.4	0.29	8.39	0.02		217	8.13	14.6	9.03	444		6.0	424.8	343.0	0.80	17.68	0.03
12.1	218	7.64	15.0	8.69	487		5.5							218	8.08	14.7	9.09	453		5.9					
13.1	219				487		5.5							219				453		5.9					
14.1	220				487		5.5							220				453		5.9					
15.1	221	7.68	14.9	8.94	492	0.57	6.0							221	8.23	14.8	9.17	496	0.55	5.9					
16.1	222	7.85	14.8	8.28	514		5.7	424.8	85.6	0.20	9.58	0.01		222	8.19	14.6	8.88	530		5.5	441.6	281.4	0.70	21.00	0.02
17.1	223	8.13	14.7	8.50	514		5.7							223	8.33	14.4	8.87	530		5.5					
18.1	224	8.19	15.0	8.55	460		5.9							224	8.38	14.7	8.91	425		6.4					
19.1	225	8.18	15.2	8.54	486		5.6							225	8.36	15.0	8.94	445		6.1					
20.1	226				486		5.6							226				445		6.1					
21.1	227				486	0.52	5.6							227				445	0.50	6.1					
22.1	228	8.17	15.4	8.80	432		6.8	432.6	152.6	0.38	20.87	0.01		228	8.39	15.2	9.11	432		6.8	452.4	289.8	0.76	34.80	0.01
23.1	229	8.40	15.0	8.46	434		6.8							229	8.59	14.8	9.20	443		6.7					
24.1	230	8.35	14.8	9.00	434	0.55	6.8							230	8.41	14.6	9.21	443	0.50	6.7					
25.1	231	8.14	14.5	9.28	514		5.9	453.4	193.2	0.47	19.15	0.01		231	8.45	14.3	9.39	370		8.2	492.0	289.8	0.78	40.37	0.01
26.1	232				547		5.6							232				378		8.0					
27.1	233				547		5.6							233				378		8.0					
28.1	234				547	0.51	5.6							234				378	0.52	8.0					
29.1	235	8.43	15.5	9.03	513		5.9	509.4	221.2	0.55	43.62	0.01		235	8.44	15.3	9.12	473		6.5	489.0	315.0	0.81	42.17	0.01
30.1	236				534		5.7							236				504		6.0					
31.1	237	8.36	15.3	8.85	534		5.7							237	8.46	15.1	9.04	504		6.0					
1.2	238	8.37	14.6	8.80	534	0.49	5.7							238	8.53	14.5	9.05	504	0.45	6.0					
2.2	239	8.38	14.9	9.00	485		6.6	525.2	268.8	0.67	38.69	0.01		239	8.57	14.7	9.27	292		11.0	559.8	322.0	0.84	60.96	0.01
3.2	240				505		6.4							240				302		10.6					
4.2	241				505	0.52	6.4							241				302	0.54	10.6					
5.2	242	8.45	15.0	9.01	491		6.4	515.0	322.0	0.74	44.42	0.01		242	8.62	14.8	9.15	294		10.6	497.4	383.6	0.86	60.53	0.01
6.2	243	8.37	15.5	8.92	512		6.1							243	8.25	15.3	9.16	397		7.9					

R3	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]	R4	pd [d]	pH [ ]	temp. [°C]	DO [mgN/L]	load NH4 [mgN/d]	removal [%]	HRT [d]	NH4 conc. [mgN/L]	NO2 conc. [mgN/L]	NAR [ ]	FA [mgN/L]	FNA [mgN/L]
7.2	244	8.27	15.2	9.03	535		5.9							244	8.25	14.9	9.28	414		7.5					
8.2	245	8.31	15.1	9.15	497	0.49	5.9							245	8.23	14.9	9.33	385	0.53	7.5					
9.2	246	8.33	15.3		472		6.2	487.2	331.8	0.75	33.14	0.02		246	8.23	15.0		413		7.0	458.8	373.8	0.84	24.54	0.02
10.2	247				491		5.9							247				447		6.5					
11.2	248				491		5.9							248				447		6.5					
12.2	249	8.34	15.2	8.91	491	0.48	5.9							249	8.44	15.1	9.06	447	0.49	6.5					
13.2	250	8.33	15.3	8.70	468		6.4	509.0	357.0	0.80	34.63	0.02		250	8.40	15.0	8.80	416		7.2	490.4	387.8	0.91	37.99	0.02
14.2	251	8.48	15.0	8.75	517		5.8							251	7.93	14.8	8.93	459		6.5					
15.2	252	8.37	15.1	8.76	517	0.49	5.8							252	8.00	15.1	8.98	459	0.52	6.5					
16.2	253	8.34	15.2	8.58	471		6.2	512.2	338.8	0.80	35.35	0.02		253	8.13	15.1	8.91	366		8.0	478.8	407.4	0.89	20.68	0.03
17.2	254	8.39	15.3	8.92	490		6.0							254	6.77	15.0	9.10	375		7.8					
18.2	255				490		6.0							255				375		7.8					
19.2	256	8.49	15.3	8.98	490	0.48	6.0							256	7.82	15.2	8.84	375	0.54	7.8					
20.2	257	8.49	15.0	8.90	343		8.3	502.2	354.2	0.87	47.17	0.01		257	7.83	14.9	8.90	365		7.8	449.8	449.4	0.93	9.76	0.07
21.2	258	8.42	14.4	8.61	349		8.1							258	7.61	14.8	9.51	377		7.5					
22.2	259	8.44	15.0	8.76	349	0.50	8.1							259	7.49	14.9	8.98	377	0.51	7.5					
23.2	260	8.04	14.9	8.66	30		####	468.6	399.0	0.84	16.32	0.04		260	7.18	14.8	8.99	60		50.0	464.6	466.2	0.89	2.27	0.31
24.2	261				0		####							261				0		####					
25.2	262				0		####							262				0		####					
26.2	263				0		####							263				0		####					
27.2	264				0	0.56	####							264				0	0.56	####					
28.2	265	6.20	14.8	9.32	497		5.6	438.0	400.0	0.80	0.23	2.50		265	6.09	14.7	9.36	463		6.0	446.4	495.0	1.00	0.18	3.99